THE

JOURNAL OF GEOLOGY

MAY–JUNE, 1911

MAGMATIC DIFFERENTIATION IN HAWAII

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INTRODUCTION

Though the Hawaiian Islands are largely basaltic, it is already apparent that they contain igneous types of considerable petrographic diversity. The species so far discovered range from ultra-femic basalts and intrusive porphyry, with less than 46 per cent of silica and less than 2 per cent of alkalies, to the phonolitic trachyte of western Hawaii, with 62 per cent of silica and more than 13 per cent of alkalies. No sediments of the ordinary silicious kinds appear to enter into the composition of the islands or of their basement. Acid crystalline rocks of the gneissic or granitic order

also seem to play no rôle in the petrogenesis of the archipelago. Hence, some of the chief complications in the history of igneous magmas which have invaded the continental plateaus, that is, complications due to the assimilation of such highly varied country-

FIG. 1.—Locality map, showing positions of some of the dated lava flows in Hawaii; also original localities of specimens chemically analyzed (dots numbered 1 to 4): 1, gabbro of Uwekahuna laccolith; 2, olivine basalt of 1852 flow; 3, andesitic basalt; 4, trachydolerite.

rocks, here seem to be absent. This relative simplicity of conditions makes the petrogenesis of a deep-sea archipelago worthy of attention quite independently of its own intrinsic importance. The problem of origin here becomes largely, though not altogether,

a matter of pure differentiation. An inspection of the results so far attained in Hawaiian petrography clearly suggests the nature of the local primitive magma, namely, basalt, and shows the march of magmatic differentiation in the main island, from that parent species to the less voluminous rock-types which have so far been discovered.

The first part of this paper is devoted to a description of rock-types forming part of a collection made by the writer in 1909. From the facts won in that reconnaissance, and from those already published in the writings of J. D. and E. S. Dana, of Lyons, Phillips, Silvestri, Cohen, Möhle, Maxwell, C. H. Hitchcock, Brigham, Dutton, Cross, and others, an induction has been made as to the probable origin of the rock species in Hawaii. A brief statement of the reasoning on which this tentative conclusion is based occupies the second part of the paper.

The four new rock analyses and the analysis of phenocrystic olivine were made by Mr. G. Steiger, chemist of the United States Geological Survey. For these excellent data the writer's sincere thanks are due to him, and to Dr. G. O. Smith, the Director of the Survey, who generously acceded to the request that this work should be undertaken by the able experts of the government laboratory.

SPECIAL PETROGRAPHY

Porphyritic gabbro of the Uwekahuna laccolith.—About two hundred meters north of the Uwekahuna triangulation station, the western wall of the Kilauean sink exhibits a patch lighter in color than the average rock in the cliff. This patch is visible from the Volcano House and the writer made an early visit to this part of the sink. (See locality marked "1" in Fig. 1.) Nearing the place, it was observed that the light-tinted rock was more massive than the lavas above and below it. Large blocks of the rock had fallen from the cliff and many were plainly seen to have been derived from the lighter-colored mass, which was gabbroid in habit. With a little trouble the writer was able to scale the cliff for the vertical distance of about 20 meters, necessary to reach the lower contact. There the gabbroid rock showed a distinctly chilled phase in a contact shell several decimeters in thickness.

The upper contact was quite inaccessible, by ordinary climbing, though it might, perhaps, be reached with the aid of a rope let down from the top of the cliff. However, the coarse grain of the holocrystalline rock and the relation of the mass to the overlying ash-beds show without question that it is intrusive. The section given in the cliff is that of a laccolith, with a width of 160 meters and a maximum thickness of about 20 meters. The ash-beds above are uparched and conformable to the upper surface of the laccolith, except at the southern end, where they are cut across at a low angle by the gabbro. The massive lava flows overlying the ash beds are little, or not at all, deformed by the intrusion. Some of the upper flows may be younger than the laccolith, but it is possible that all the overlying flows are the older and that the lack of deformation in them is due to the lateral crowding and condensation of the loose ash-beds by the laccolithic magma.

The gabbroid body may conceivably represent the crystallized product of a subterranean lava stream of great length, but its deformation of the overlying ash-beds is characteristic of laccolithic intrusion and it seems just to describe the mass as a true laccolith.

The intrusive rock is dark gray in color, and slightly porous. It is porphyritic, with phenocrysts of olivine. These are so numerous that the rock appears, at first glance, to be somewhat coarsely granular. In the hand-specimen the phenocrysts appear roundish, and only rarely idiomorphic. Some of them are of the usual olive-green color, but most are iridescent on the surfaces of fracture, with the beautiful blue, green, and bronze tints of a peacock's feather. Though the rock in general is extremely fresh, this iridescence seems to be due to an incipient alteration of the olivine to serpentine, which is mixed with numerous, minute grains of iron ore.

Under the microscope, the idiomorphism of the nearly colorless, pale brownish olivine is more clearly manifest. It occurs in individuals reaching 4 mm. or more in length. The ground-mass is composed of plagioclase, augite, ilmenite, and magnetite; the chemical analysis of the rock shows that a little apatite must be present, but not a single crystal of it was demonstrable in the thin section. The ground-mass varies irregularly from the hypidio-

morphic-granular to the diabasic. The thin-tabular plagioclase, reaching 1 mm. in longest diameter, seems to be throughout the basic labradorite, $Ab_2\ An_3$. The pale brownish augite has normal habit, the major diameters reaching 0.8 or 1.0 mm. There is nothing unusual about the minerals of this rock and further descriptive details are superfluous.

An analysis of the rock, by Mr. G. Steiger, gave the result shown in col. 1 of Table I.

TABLE I

	1	1a	2
SiO_2	46.59	.777	48.13
TiO_2	1.83	.023	.87
Al_2O_3	7.69	.075	6.50
Fe_2O_3	2.20	.014	2.01
Cr_2O_3	.13	.001	.....
FeO	10.46	.145	11.73
MnO	.18	.002	.08
NiO	.12	.001	.....
MgO	21.79	.545	21.01
CaO	7.41	.132	6.17
Na_2O	1.33	.022	1.15
K_2O	.28	.003	.58
H_2O-	.04	....	1.62
H_2O+	.37	....	
P_2O_5	.11	.001	.15
CO_2	None	....	.....
SO_3	None	....	.....
BaO	None	....	.....
SrO	None	....	.....
ZrO_2	None	....	.....
	100.53		100.00
Sp. gr.	3.001		

Calculated Norm of 1.

Orthoclase	1.67
Albite	11.53
Anorthite	13.90
Diopside	17.48
Hypersthene	17.06
Olivine	31.22
Ilmenite	3.50
Magnetite	3.25
Chromite	.22
Apatite	.31
Water	.41
	100.55

1 Porphyritic gabbro of the Uwekahuna laccolith.

1a Molecular proportions in 1.

2 Average analyses of three typical wehrlites.

Using the chemical analysis and the Rosiwal optical method, the minerals have been calculated to form the following weight percentages:

Olivine	40.0
Augite	31.0
Labradorite	27.0
Magnetite and ilmenite	1.7
Apatite	.3
	100.0

In the Norm classification the rock falls in the domagnesic subrang, wehrlose, in the permiric section, wehrliase, permirlic rang, wehrlase, and section hungariare, of the dofemane order, hungarare.

According to the accepted Mode classification the rock is an ultra-femic porphyritic olivine gabbro or gabbro porphyrite. The analysis is very similar to the average of three typical wehrlites entered in Part II of Osann's *Beiträge zur chemischen Petrographie*. See column 2 of the accompanying Table I.

Ultra-femic olivine basalt, flow of 1852.—Following the trail from the Volcano House to Mauna Kea, the writer crossed the lava which, in 1852, flowed out on the Hilo slope of Mauna Loa. The trail traverses this lava at the 6,100-foot contour (see locality "2" in Fig. 1), where the flow is about 1.5 kilometers in width. The lava is of the aa or block type and much work with sledge hammers was necessary to make a trail passable even for the hardy pack-animals of the island. The broken rock is, of course, quite fresh, and its numerous olivine phenocrysts, of unusually great size and of beautiful color and brilliance, made a remarkable effect for the eye as one walked or rode over the lava. The development of phenocrystic olivine is greater in this flow than in any other seen by the writer during several hundred miles of travel in Hawaii.

The hand-specimens of the lava have a dark-gray, lithoidal ground-mass, in which the abundant, bright yellowish-green olivines are conspicuously set. As usual with the aa type of lava, the gas pores are large and irregularly distributed through the rock. They were elongated and flattened during the flow of the stiffening lava and the longer diameters of the pores reach three or more centimeters in length. The idiomorphism of the olivine is often manifest to the unaided eye, and is still more evident under the microscope. The individual crystals are often more than one centimeter in diameter. No other mineral is phenocrystic.

The microscope shows a rather surprising contrast in the grain of the ground-mass, which is of diabasic structure, with thin tables of plagioclase, seldom over 0.1 mm. in length, separated by augite granules of even smaller diameters. Magnetite and prob-

ably ilmenite form the only other visible constituents, though a little apatite must occur. No glass and no sulphide mineral could be found in the ground-mass.

The olivine includes a little magnetite, in small euhedral and anhedral crystals. A few brown, roundish inclusions may be glass. In thin section the olivine is nearly colorless with a gray tinge. It was easily isolated and then freed of impurities except for the minute inclusions described. Its analysis, by Mr. Steiger, gave the following result:

		Mol.	Calculated Composition	
				Per cent
SiO_2	40.42	.670	Forsterite	82.29
TiO_2	.08	.001	Fayalite	15.94
Al_2O_3	.32	.003	Tephröite	0.20
Fe_2O_3	.15	.001		98.43
Cr_2O_3	.18	.001		
FeO	11.44	.159	Anorthite	0.97
MnO	.10	.001	Magnetite	0.23
NiO	.34	.005	Ilmenite	0.15
MgO	47.08	1.168	Chromite	0.22
CaO	.23	.004	NiO	0.34
	100.34			1.91
Sp. gr.	3.369		Grand total	100.34

So far as known to the writer, this is the only total analysis of any Hawaiian olivine yet made. Penfield and Forbes found 10.3 per cent of FeO in olivine collected by J. D. Dana on the south-eastern shore, south of Hilo. The optical angle (2V) for this mineral was calculated to be 91° 2′, and the authors found that chrysolites containing about 12 per cent of FeO show a value of 90° for 2V in yellow light.[1] The olivine now described has 11.44 per cent of FeO, and hence it would be extremely difficult to be quite certain whether the mineral is positive or negative. No special work has been expended in the attempt to determine that point.

The minute plagioclase tables of the ground-mass gave maximum extinctions corresponding to the mixture Ab_{45} An_{55}. The augite is pale, practically colorless in thin section, and has no noteworthy

[1] S. L. Penfield and E. H. Forbes, *Amer. Jour. Sci.*, I (1896), 133.

peculiarities. A study of the chemical and mineralogical analyses showed that it must be rich in FeO and relatively poor in MgO. The magnetite and ilmenite are abundant in the ground-mass.

Mr. Steiger's analysis of the rock gave the proportions shown in Table II.

TABLE II

	1	1a
SiO_2	48.57	.810
TiO_2	1.48	.019
Al_2O_3	10.51	.103
Fe_2O_3	2.19	.014
Cr_2O_3	.10	.001
FeO	9.45	.132
MnO	.16	.001
NiO	.08	.001
MgO	17.53	.438
CaO	8.06	.144
Na_2O	1.50	.026
K_2O	.34	.004
H_2O-	.10	....
H_2O+	.37	....
P_2O_5	.19	.001
CO_2	None	....
	100.72	
Sp. gr.	3.065	

Calculated Norm	
Orthoclase	2.22
Albite	13.62
Anorthite	20.29
Diopside	15.11
Hypersthene	23.98
Olivine	18.49
Ilmenite	2.89
Magnetite	3.25
Apatite	.31
Water	.47
	100.63

1 Ultra-femic olivine basalt, lava flow of 1852.
1a Molecular proportions in 1.

Using the Rosiwal method, checked by the analyses, the Mode (weight percentages) was calculated to be:

Olivine	32.0
Augite	27.0
Labradorite	35.7
Ilmenite	2.5
Magnetite	2.5
Apatite	.3
	100.00

Assuming the probable values of the specific gravity for each mineral, the specific gravity of the rock was calculated to be 3.16, which agrees satisfactorily with the actual value, 3.065, found by the proper weighing of coarse powder of the rock.

In the Norm classification the rock enters the hitherto unnamed

domagnesic subrang, in the permiric section and permirlic rang of the dofemane order, hungarare. If a name for this type in the Norm classification is desired, the subrang may be called *hilose*, from the name of the chief port of the island, Hilo. The corresponding names for the rang-section and rang would be *hiliase* and *hilase*. The hitherto unnamed section of the order may be called *hawaiiare*.

According to the Mode classification the rock is an ultra-femic olivine basalt of an extreme type. In both chemical and mineralogical analyses it approaches the still more abnormal type represented in the Uwekahuna laccolith.

Andesitic basalt, upper slope of Mauna Kea.—On the eastern side of Mauna Kea, from the 6,000-foot contour to about the 12,000-foot contour, the abundant lava flows seem to be very uniformly composed of a rock species which is intermediate between typical olivine basalt and a true augite andesite. These lavas are almost entirely of the aa or blocky type; pahoehoe surfaces are only locally developed and, within the area described, seldom, if ever, show the perfection so often illustrated in Mauna Loa. Among the specimens collected, one taken at the 11,000-foot contour (see locality "3" in Fig. 1), 4,500 meters S 75° E of the summit of Mauna Kea, was selected for chemical analysis. Its description would doubtless apply, with but unimportant change, to the average lava of all this part of the great volcano.

The rock is dark gray, fresh, and strongly vesicular, again showing the great irregularity in the size and distribution of the vesicles, which is usual with aa lava. The only minerals microscopically visible in the dense ground-mass are a few phenocrysts of yellowish-green olivine and tabular plagioclase, with maximum diameters of 2 mm. and 3 mm. respectively. In thin section a few idiomorphic phenocrysts of augite, reaching 1 mm. in length, are to be seen. Estimates made by the Rosiwal method show that the olivine phenocrysts form no more, or little more, than one per cent of the rock by weight, and that the augite phenocrysts occur in about the same proportion. The very abundant plagioclase phenocrysts have cores averaging about $Ab_1 An_1$ in composition. They are often surrounded by a very thin shell of oligoclase

averaging $Ab_7 An_3$, as indicated by zero extinction on (010). That shell is surrounded by a still thinner, outermost shell, which gives an extinction of about $+5°$ on (010) and is either a more acid oligoclase or else orthoclase.

The ground-mass has a pilotaxitic to diabasic structure and consists of plagioclase, augite, and magnetite, each in high proportion. A few round granules of olivine may also be discerned. The plagioclase is often zoned, with a somewhat larger relative development of the acid shells. Again, the outermost shell may, in many cases, be alkaline feldspar, but the very fine grain prevents its actual demonstration. No sulphide mineral was visible in the rock.

Mr. Steiger's analysis yielded the result shown in column 1 of Table III.

TABLE III

	1	1a	2
SiO_2	49.73	.829	49.19
TiO_2	3.05	.038	1.72
Al_2O_3	16.39	.161	14.02
Fe_2O_3	7.58	.048	5.62
FeO	3.98	.056	8.68
MnO	.23	.003	.54
MgO	4.06	.101	6.42
CaO	7.17	.128	9.10
Na_2O	4.12	.066	3.24
K_2O	1.03	.020	1.04
H_2O-	.81	....	} .74
H_2O+	.54	....	}
P_2O_5	.84	.006	.28
CO_2	None	....	.....
BaO	.03	....	.....
SrO	None	....	.....
NiO	.04	....	.....
Cr_2O_3	None	....	.....
ZrO_2	.03	....	.....
SO_3	None	....	.....
S	None	....	.....
	100.53		100.59
Sp. gr.	2.911		

Calculated Norm of 1

Quartz	1.86
Orthoclase	11.12
Albite	34.58
Anorthite	20.85
Diopside	6.78
Hypersthene	6.80
Ilmenite	5.78
Magnetite	4.87
Hematite	4.32
Apatite	1.86
Water, etc.	1.45
	100.27

1 Andesitic basalt, lava flow at 11,000-foot contour of Mauna Kea.
1a Molecular proportions in 1.
2 Average composition of normal Hawaiian basalt.

By the Norm classification the rock enters the dosodic subrang, andose, in the alkalicalcic rang, andase, of the dosalane order, germanare.

According to the Mode classification, it is an andesitic basalt, transitional in type between olivine basalt and augite andesite. Its specific gravity was determined on a specimen which had been coarsely powdered to avoid an error due to the porosity of the rock. For comparison the calculated average for the basalt of Hawaii is given in column 2.

Trachydolerite of summit flows, Mauna Kea.—Brigham and others long ago noted the occurrence of "clinkstone" at the top of Mauna Kea, and the present writer had opportunity to make some study of this rock in place during the 1909 reconnaissance. Near the 13,000-foot contour, he found several flows of lava of much lighter color than the staple olivine basalts of Hawaii, or than the abundant andesitic basalt just described. These flows all seem to be short, generally less than one kilometer in length. Their terminal scarps have been little affected by frost or other weathering agents, and the steepness of these scarps indicates a notable degree of viscosity during the outflow. In some cases these flows could be seen to have emanated from the fissures in the summit cinder-cones. Though the pyroclastic material of the cones is generally altered (to deep brown and red tints), it appears to be chemically identical with that composing the always fresh, light-colored flows.

The "clinkstone" habit is due largely to a noteworthy lack of vesicles in the lava. Though some large gas-pores always occur in the thin surface shell of each flow, its interior is often nearly or quite free from even small pores. This homogeneity of the rock is, doubtless, chiefly responsible for the extremely sonorous, metallic sound given out when the lava is broken by the hammer.

For special examination, typical specimens were taken from a flow which issued from the eastern flank of the cinder-cone named "Poliahu" on the government map, at a point about 350 meters north of the summit pond. The description of the lava may be based on one specimen, which has been chemically analyzed.

The rock is of a fairly light, slate-gray color, is non-porous, very dense, but holocrystalline. A few thick tables of plagioclase, from 1 mm. to 2 mm. in length, represent the only constituent determi-

nable to the unaided eye. There is merely a hint at flow-structure, registered in a rude parallelism of these phenocrysts.

Under the microscope it is seen that a few, small, anhedral olivines, and somewhat more numerous augite crystals—none, in either case, surpassing 1 mm. in greatest diameter—are to be added to the abundant plagioclase (averaging labradorite, $Ab_1 An_1$) in the list of phenocrysts.

The ground-mass shows a confused crystallization of augite, magnetite, and apatite, in a dominant felt of feldspar. A few grains of an allanite-like mineral, pleochroic in tones from deep brown to pale greenish-brown, form the only other accessory material. No sulphide is visible in thin section. Most of the ground-mass feldspar is plagioclase—acid labradorite or basic andesine—twinned on the albite law. Another feldspar arranged interstitially in relation to the plagioclase has the low double refraction and lack of twinning characteristic of orthoclase. This mineral occurs in such minute individuals that a full demonstration of its nature has not been possible. Many of the labradorite phenocrysts are surrounded with shells of alkaline feldspar with extinctions on (010) ranging from $+5°$ to $+9° 30'$, suggesting orthoclase and soda-orthoclase, and it is very probable that both of these represent the last product of crystallization in the ground-mass. The total alkaline feldspar does not form much more than 15 per cent of the rock by weight.

Mr. Steiger's analysis of this rock gave the proportions shown in col. 1 of Table IV.

By the Norm classification the rock is to be referred to andose, the same subrang as that calculated for the andesitic basalt just described. According to the Mode classification, this rock, containing an essential amount of alkaline feldspar, is best included among the trachydolerites, as defined by Rosenbusch, though near the basaltic end of that series. In column 2 of Table IV the average of the 34 analyses of trachydolerites, named as such in the last edition of Rosenbusch's *Elemente der Gesteinslehre*, is given for comparison. Column 3 gives Lyons' analysis of a more alkaline, less femic, trachydoleritic type from the neighboring volcanic pile in Kohala.[1]

[1] A. B. Lyons, *Amer. Jour. Sci.*, CLII (1896), 424.

Lherzolitic nodules in the summit lavas of Mauna Kea.—The chief difference between the andesitic basalt and the trachydolerite is mineralogical; orthoclase is an essential constituent in the latter, and has wholly, or almost wholly, failed to individualize in the basalt. The two types are almost alike chemically. They also resemble each other in carrying rather numerous ultra-femic nodules of all sizes up to 10 cm. in diameter. These are always rounded and usually roughly spherical, of coarse grain, and of a

TABLE IV

	1	1a	2	3
SiO_2	50.92	.849	49.20	58.06
TiO_2	2.55	.032	1.68	1.88
Al_2O_3	17.59	.173	16.65	18.21
Fe_2O_3	3.80	.024	4.76	4.87
FeO	6.69	.093	5.36	2.01
MnO	.20	.001	.55	.36
MgO	3.90	.097	4.43	1.59
CaO	6.97	.125	7.74	3.29
Na_2O	4.28	.069	4.54	6.12
K_2O	1.86	.020	3.19	2.75
H_2O-	.35	....	1.30	.....
H_2O+	.79	....		.....
P_2O_5	.40	.003	.60	.65
CO_2	None	.....	.....	.....
NiO	None	.....	.....	.....
Cr_2O_3	None	....	.....	.....
CuO, etc.	.....	.....	.....	.20
	100.30		100.00	99.99
Sp. gr.	2.761			

Calculated Norm of 1	
Orthoclase	11.12
Albite	36.16
Anorthite	23.35
Diopside	6.98
Hypersthene	7.21
Olivine	2.98
Ilmenite	4.86
Magnetite	5.57
Apatite	.93
Water	1.14
	100.30

1 Trachydolerite, lava flow at 13,000-foot contour on Mauna Kea.

1a Molecular proportions in 1.

2 Average of 34 analyses of trachydolerites named as such in the third edition of Rosenbusch's *Elemente der Gesteinslehre.*

3 "Andesite" from Waimea, Kohala district, in northwestern Hawaii.

dark green or brownish-green color. They seem to be rather uniformly composed of dominant olivine, much diallage, subordinate or accessory plagioclase, and a little magnetite or ilmenite. Apatite has not been demonstrated in thin section.

The nodules occur in the trachydolerite of the cinder-cones as well as of the adjacent flows. In a few cases observed, the nodules of the cinder-cones formed ellipsoidal bodies without any adhering trachydolerite, as if each of these nodules represents a solid mass exploded out of the vent and freed from liquid magma by the

violence of the explosion. More generally, the nodules occur in projectiles largely composed of the normal trachydolerite. The specific gravity of one ellipsoidal nodule about 8 cm. in length was found to be 3.316; it is almost entirely free from feldspar.

The nodules inclosed in lava are best displayed in the frost-riven felsenmeer surrounding the summit pond. One of these was sectioned and specially studied. The plagioclase was found to have the composition of acid anorthite, $Ab_1 An_9$. A few small tables of the feldspar and rare granules of olivine are inclosed in the diallage, but in general, the anorthite is interstitially developed between the olivine and diallage crystals, which seem to have crystallized nearly simultaneously and after the iron ore. The pyroxene is much more often idiomorphic than is the olivine. The specific gravity of this nodule is 3.111.

The Rosiwal method afforded the following estimate of its weight percentages:

Olivine	62
Diallage	26
Anorthite	11
Magnetite and ilmenite	1
	100

Assuming the olivine to have the same composition as the olivine in the lava flow of 1852, and the diallage to have the average composition of basaltic augite,[1] the nodule was calculated to have, approximately, the composition shown in column 1 of Table V.

TABLE V

	1	2
SiO_2	43.4	43.78
TiO_2	.3	.12
Al_2O_3	5.5	5.02
Fe_2O_3	1.5	5.18
FeO	8.8	4.77
MgO	32.8	33.08
CaO	7.4	6.62
Na_2O	.3	1.06
$MnO+K_2O+P_2O_5$	....	.37
	100.0	100.00

[1] See *Journal of Geology*, XVI (1908), 410.

Column 2 gives the average composition of four typical lherzolites.[1] In spite of any uncertainties as to the exact compositions of the femic minerals, it is clear that the nodule is, chemically, a lherzolite.

The writer believes that these nodules are not exotic, but represent segregations in their respective magmas just as truly as do the olivine phenocrysts. Easy transitions in size are to be found, in the field, between large, single phenocrysts of olivine and the largest olivine nodules observed.

Notes on other lava flows, studied microscopically.—On the trail from the Volcano House to Mauna Kea, at about the 6,000-foot contour (see Fig. 1), the flow of 1880–81 was found to be olivine basalt of the pahoehoe type. The adjacent flow of 1855 is similarly composed but has local aa phases. Still farther north the trail crosses the "ancient flow" shown on the government map (marked "ancient" in Fig. 1); this is an olivine basalt with typical aa habit. At the wagon-road between Waimea and Kailua, the great flow of 1859 is an olivine-poor to olivine-free basalt with both aa and pahoehoe phases.

Projected blocks at Kilauea and Hualalai.—E. S. Dana has already described the common, basaltic types of rock represented in the solid projectiles thrown out in the rare explosions which have occurred at Kilauea.[2] The present writer has made a microscopic examination of seven different specimens of the projectiles sampled at intervals along the edge of the Kilauean sink from Uwekahuna to Kilauea Iki. All of them are holocrystalline and they are non-vesicular or else nearly free from pores. In the coarser blocks the pores are true miaroles, into which the feldspar and augite, showing crystal facets, have grown. The rock species included in this small collection are: basalt poor in olivine; typical olivine diabase; olivine-free diabase; and a typical, relatively coarse-grained olivine-free gabbro.

Of these, the gabbro is the only type worthy of special remark. It composes several of the projectiles occurring on the road from the Volcano House to Kilauea Iki, near Waldron's Ledge. The

[1] See *Proc. Amer. Acad. Arts and Sciences*, XLV (1910), 226.

[2] See J. D. Dana, *Characteristics of Volcanoes* (New York, 1891), 344.

visible blocks are all angular, quite fresh, and 20 to 50 cm. in greatest diameters. No olivine is visible in the fairly dark-gray, granular rock, either in the field or under the miscroscope. The essential constituents are labradorite, Ab_2 An_3, and a strongly tinted, greenish-brown, non-pleochroic augite, with an unusual amount of iron ore, probably ilmenite. Apatite in needle form is very abundant; therein this rock contrasts with nearly every Hawaiian rock so far studied in thin section. The stout augite prisms, which lack the diallage parting, reach 4 mm. in length; the thick tables of labradorite are often 5 mm. in length and the plates of ilmenite measure 1 mm., or less, to 5 mm. in length. The structure of the rock is not basaltic or diabasic, but typically hypidiomorphic-granular.

On the summit of Hualalai the writer sampled three projected blocks which occur in a thin pyroclastic deposit veneering this lava-formed (olivine-basalt) volcano. Two of them are holocrystalline equivalents of the normal olivine basalt of the island. The third is a coarsely granular rock almost identical in composition and grain with the type forming the laccolith at Uwekahuna; it is an ultra-femic gabbro, with high idiomorphism in the abundant olivine.

Average composition of Hawaiian basalt.—Of the extant analyses of the basalts from the main island, nineteen, which were made from fresh and typical material, have been selected for the purpose of computing the average composition of the dominant rock type of the island. Most of these analyses are quoted in C. H. Hitchcock's *Hawaii and Its Volcanoes* (Appendix D). Ten are taken from O. Silvestri's paper in the *Bolletino del R. Comitato Geologico Italiano* (XIX [1888], 185); four from E. Cohen's paper in the *Neues Jahrbuch für Mineralogie*, etc. (1880; II, 23); and four from A. B. Lyons' paper in the *American Journal of Science* (II [1896], 424). Mr. Steiger's analysis of the 1852 flow and his analysis of the chemically similar porphyry forming the small laccolith at Uwekahuna, Kilauea, are also included, making twenty analyses in all.

The calculated average is shown in the first column of Table VI, where the second column gives the writer's result in averaging

198 analyses of fresh basalts taken from Osann's great compilation for the world (analyses published between 1884 and 1900).

TABLE VI

	Average Hawaiian Basalt	Average World Basalt
SiO_2	49.19	49.06
TiO_2	1.72	1.36
Al_2O_3	14.02	15.70
Fe_2O_3	5.62	5.38
FeO	8.68	6.37
MnO	.54	.31
MgO	6.42	6.17
CaO	9.10	8.05
Na_2O	3.24	3.11
K_2O	1.04	1.52
H_2O	.74	1.62
P_2O_5	.28	.45
	100.59	100.00

The close correspondence of the two averages is obvious at a glance. In fact, it has been found that the greater the number of reliable analyses included, the nearer the Hawaiian average approaches the world average. Though perfect averages might show the former to be slightly the more femic of the two, it is certain that the staple igneous type in the mid-oceanic Hawaii are chemically very similar to the average basaltic magma poured out on the continental plateaus.

THEORETICAL CONSIDERATIONS

Origin of the ultra-femic types.—In columns 1 and 2 of Table VII the analyses of the Uwekahuna laccolith and of the 1852 lava flow are respectively entered. Column 3 gives the mean of these two analyses. Column 5 gives the average analyses of four typical lherzolites, calculated as water-free. Column 6 shows the calculated composition of the average Hawaiian basalt, while column 4 gives the mean of columns 5 and 6.

A comparison of the markedly similar columns 3 and 4 suggests that the ultra-femic magmas of the island are due to the mixture of a large amount of the ferromagnesian and cafemic (calcium-iron-magnesium) constituents of the basalt with the average basalt itself, though, of course, not necessarily in absolutely equal pro-

portions for the two parts of the mixture. Such a mixture could occur in the main volcanic vents at great depth, provided that the ferromagnesian and cafemic molecules settled down from the magma in the upper part of the vent, where gravitative differentiation was taking place.

This explanation of the ultra-femic phases is favored by the consideration that no fact in the field relations opposes the assumption of a very deep, direct source for these heavy magmas. The flow of 1852 emanated from a fissure in Mauna Loa, about 1,300 meters below the top of the main conduit of the island; and the laccolithic body exposed in the wall of Kilauea is 3,000 meters

TABLE VII

	1 Laccolithic Porphyry	2 Flow of 1852	3 Mean of 1 and 2	4 Mean of 5 and 6	5 Average Lherzolite	6 Average Hawaiian Basalt
SiO_2	46.59	48.57	47.58	46.65	43.78	49.19
TiO_2	1.83	1.48	1.66	.92	.12	1.72
Al_2O_3	7.69	10.51	9.10	9.52	5.02	14.02
Fe_2O_3	2.20	2.19	2.20 } 12.15	5.40 } 12.12	5.18	5.62
FeO	10.46	9.45	9.95 }	6.72 }	4.77	8.68
MnO	.18	.16	.17	.30	.06	.54
MgO	21.79	17.53	19.66	19.75	33.08	6.42
CaO	7.41	8.06	7.74	7.86	0.62	9.10
Na_2O	1.33	1.59	1.46	2.15	1.06	3.24
K_2O	.28	.34	.31	.67	.30	1.04
H_2O	.41	.47	.44	.37	.....	.74
P_2O_5	.11	.19	.15	.15	.01	.28
Cr_2O_3 etc.	.25	.18	.21	.....	.....	.....
	100.53	100.72	100.63	100.46	100.00	100.50

below the same level. In either case, the level in the conduit where it was tapped to form the erupted body may have been several kilometers still lower down in that conduit.

Origin of the less femic types.—The hypothesis that the ultra-femic rocks represent the products of mixture of the average basalt with the ferromagnesian and cafemic substances (more specifically the molecules represented in the phenocrysts of the normal basalt) settled down from higher levels in the main Hawaiian vent, implies that more salic and more alkalic magma is formed at those higher levels. According to the thoroughness of the gravitative differentiation, the less dense magmas would vary in the degree in which

they would be more salic and alkalic than the parent basalt. As a matter of fact, a goodly number of such derived magmas seem to be represented in Hawaii. Table VIII, columns 2–6, shows the chemistry of the principal types to which this mode of origin may be, at least tentatively, ascribed.

TABLE VIII

	1	2	3	4	5	6
SiO_2	49.19	49.73	50.92	58.06	61.64	62.19
TiO_2	1.72	3.05	2.53	1.88	.....	.37
Al_2O_3	14.02	16.39	17.59	18.21	.....	17.43
Fe_2O_3	5.62	7.58	3.80	4.87	.....	1.65
FeO	8.68	3.98	6.69	2.01	.....	2.64
MnO	.54	.23	.20	.36	.....	.32
MgO	6.42	4.06	3.90	1.59	.....	.40
CaO	9.10	7.17	6.97	3.29	.....	.86
Na_2O	3.24	4.12	4.28	6.12	.....	8.28
K_2O	1.04	1.93	1.86	2.75	.....	5.03
H_2O	.74	1.35	1.14	.....	.....	.53
P_2O_5	.28	.84	.40	.65	.....	.14
NiO, etc.	.....	.10	.....	.20	.....	.09
	100.59	100.53	100.30	99.99	.....	99.93
Sp. gr.	.....	2.911	2.761	.....	.....	2.627††

†† Determined from hand-specimen collected by the writer. All three rocks for which specific gravities are given, are holocrystalline.

1 Average analysis of twenty basaltic types in Hawaii.

2 Andesitic basalt of Mauna Kea.

3 Trachydolerite of summit, Mauna Kea.

4 "Andesite" (trachydolerite) of Waimea, Kohala district (analyzed by A. B. Lyons, *Amer. Jour. Sci.*, II [1896], 424).

5 "Augite Andesite from the Sandwich Islands" (silica determined by E. Cohen, *Neues Jahrbuch für Mineralogie, etc.* [1880; II, 38]).

6 Phonolitic trachyte of Puu Anahulu (described by W. Cross, *Journal of Geology*, XII [1904], 510).

On p. 53 of the paper by Cohen, for which the reference has been given, it is stated that in the rock collection there described, four other occurrences of "typical augite andesites" in Hawaii are represented. Two of the specimens were taken on Mauna Kea; the other two were collected on this island, but the labels failed to give their exact localities. No analyses were made of these specimens, but, of course, one may trust Cohen's well-known skill in diagnosis and place all four rocks among the more salic types of Hawaii.

From the table it seems clear that the strongly alkaline trachyte

of Puu Anahulu and the "andesite" of Waimea are consanguineous and that transitional types connect them with the distinctly subalkaline, normal basalt of the island. The steady decrease of the iron oxides, magnesia, and lime, and the corresponding increase in silica, alumina, and alkalies are as systematic as could be expected in a syngenetic series derived by the process of differentiation already in part described.

The norms calculated for the analyzed types tell the same story. They are summarized in the form here given:

	Average Hawaiian Basalt	Andesitic Basalt of M. Kea	Trachydolerite of M. Kea	Andesite of Waimea	Trachyte of Puu Anahulu
Salic	53.94	68.41	70.63	85.09	86.74
Femic	45.76	30.41	28.53	14.75	12.45

Calculation shows that the alkalic members of the series were probably not formed by a mere subtraction of ferromagnesian and cafemic, phenocrystic material from the normal basaltic magma. On the other hand, a positive addition of the alkalies seems to have occurred when the more silicious types were developed.

The concentration of the alkalies in the upper part of an initially basaltic vent may conceivably be due to two principal causes. In the first place the feldspathic or feldspathoid matter of the basalt might individualize in liquid phases or as plastic or rigid crystals, and, because of the low density of any of these phases, rise in the magma column, just as the individualized olivine or augite (in liquid or solid phases) must sink. Or, secondly, the volcanic vent may become temporarily enriched in emanating gases, which, as they rise, bring the alkalies with them in loose combination.

Of these two possible causes the partial control by rising volatile substances seems to be specially clear in intrusive bodies. The writer has suggested that most of the alkaline rock types have been derived from subalkaline magma through the solution of limestone or other carbonate-bearing sediments.[1] Thereby the subalkaline magma is not only fluxed and so prepared for drastic

[1] *Bulletin Geological Society of America*, XXI (1910), 87–118.

differentiation, but the carbon dioxide introduced from the sediment carries the alkalies with it as the gas rises through the magma. An instructive series of experiments by Giorgis and Gallo bear on this suggestion. They mixed the powders of various recent Vesuvian lavas with water, and passed a current of carbon dioxide through each mixture for a period of two months. Analyses showed that the powders lost, on the average, 37 per cent of the soda originally contained, the remaining constituents being but little altered in amount.[1] At high temperatures the upward transfer of the alkali would presumably be much more rapid.

In the case of the Puu Anahulu trachyte or in that of the Waimea "andesite," the principal factor in the differentiation may have been the solution of coral or foraminiferal limestones, such as are known to be interbedded with the older lavas of the archipelago. That the normal magma of the archipelago has been locally affected by such solution is suggested by the occurrence of melilite and nephelite in the basalts of Maui and Oahu, the melilite indicating an excess of lime and the nephelite showing such desilication of the salic part of the magma as is expected when it dissolves foreign lime. The carbon dioxide entering the primary basaltic magma because of this solution of sedimentary rock would belong in the "resurgent" class of emanations. A special concentration of juvenile carbon dioxide in a basaltic vent would, in an analogous way, tend to concentrate the alkalies of the basalt at the top of the vent.

This hypothesis, that the decidedly alkaline rocks of Hawaii have been derived from the normal, subalkaline basalt through gravitative differentiation in the volcanic conduits, is supported by the intimate field-association of the two classes of rocks, and by the fact that the alkaline bodies are all of very small volume as compared with the known mass of normal basalt in Hawaii. The first-mentioned relation is obvious; the second is already clear, even though the island has been covered only by reconnaissance journeys. It is practically certain that the trachyte of Puu Anahulu and vicinity, the most salic type and one very conspicuous in the field, can be exposed at but very few and small

[1] G. Giorgis and G. Gallo, *Gazetta* (1906) [I], 137.

areas at the present surface of the island. As expected on the hypothesis, the alkaline types more nearly approximating the average basalt in composition are much more voluminous than the extreme phonolite-trachyte member of the series. In Mauna Kea, at any rate, the trachydoleritic representative of the alkaline species seems to be confined to the summit plateau of the volcano, that is, to the region where it should occur if it were due to the vertical differentiation of the basalt.

On the other hand, the dominant rocks on the broad summits of Mauna Loa and Hualalai, and of Haleakala, in Maui, are normal basalts, often rich in phenocrystic olivine.[1] There is no doubt that the conditions were unfavorable to important differentiation during most of the time engaged in the building of these giant volcanoes. Similarly, the lava of the active vent at Kilauea is basaltic and apparently has always been of that normal composition.

One reason for this contrast with Mauna Kea in its latest stage is probably connected with difference of temperature, for the differentiation of any of the commoner earth magmas seems to take place only within a comparatively narrow temperature range occurring just above the "point" of solidification. That the average temperature of the latest Mauna Kea vents was actually lower than that characteristic of the active Mokuaweoweo on Mauna Loa is suggested: (*a*) by the smaller size of the pipes on Mauna Kea; (*b*) by the far greater abundance of pyroclastic material on Mauna Kea; and (*c*) the correlative high viscosity of the short, stubby flows on Mauna Kea. The latter were more viscous than the average flow on the summit of Mauna Loa, not merely or chiefly because of difference in chemical composition.

But a probably much stronger control is to be found in the

[1] E. S. Dana describes a group of "clinkstone-like basalts" (specific gravity, 2.82–3.00), free from olivine or very poor in it, which were collected at the summit of Mauna Loa. These may represent incipient differentiation even at Mokuaweoweo. Another, highly olivinic group of basalts (specific gravity 3.00–3.20) are, however, associated in great volume. (See J. D. Dana, *Characteristics of Volcanoes* [New York, 1891], p. 319.) The present writer found a similar variation in the basalts at the summit of Haleakala, which are cut by dikes of compact, olivine-free rock suggestively like the trachydolerite of Mauna Kea.

inhibiting convection which is so powerful in highly fluid columns like those of the active Mokuaweoweo or Kilauea. In a paper published in the current volume of the *Proceedings of the American Academy of Arts and Sciences*, the writer has indicated the probable cause of the very energetic stirring visible in the Kilauea lava column. The action is there called "two-phase convection," as it depends on vesiculation of the lava in depth. The gas-bubble phase is formed through supersaturation of the liquid with juvenile volatile matter. A small amount of vesiculation in depth must lend much buoyancy to the magma, which rushes up the conduit in periodic gushes; its place is taken by sinking magma that has been rendered more dense by the escape of its included gas at the surface. This type of stirring—incomparably more effective than thermal convection can be in such a column—keeps the vent open by transferring the abyssal heat to the zone of radiation; and as well, tends to prevent differentiation because of the continuous, thorough mixing of components in the magmatic column. A dormant state is introduced when the special supply of gas is largely exhausted. Then two-phase convection is slowed down, and if the other conditions permit, gravitative differentiation may affect the column more or less. Revival of activity is the result of a renewed concentration of juvenile gases rising into the conduit from the feeding magma chamber. The consequent strengthening of two-phase convection means a speedy remixing of the products of differentiation in the column. Hence, in such hot vents as those at Kilauea, Mokuaweoweo, or Matavanu, outflows of highly differentiated lavas are not to be expected.

When Mauna Kea was approaching extinction, its magmatic column or columns, characterized by increasing viscosity and perhaps less charged with juvenile gases, were less stirred by two-phase convection. In relative quiet they differentiated to a slight extent, giving a trachydoleritic type as the upper, salic pole. The gases became dissipated at the craters, and the effluent lavas of this latest phase of the volcanic pile are "clinkstones" because comparatively free of gas-pores. The explosions which formed numerous cinder-cones at the summit may have been due to the inhibition and superheating of meteoric

water, as well as to the latest, violent expulsion of the juvenile gases from the increasingly viscous magma.

Little is known of the detailed geology of the Kohala district, but the abundance of cinder-cones on the heights of this other great pile suggest a differentiation history resembling that sketched for Mauna Kea. However, the strongly alkaline "andesite" of Waimea, like the phonolitic trachyte of Puu Anahulu, may represent limestone-fluxing as a leading condition for such specially advanced differentiation of the basaltic magma.

Parallel differentiation in other oceanic islands.—Weber's recent study of the Samoan lavas, including those from Savaii, shows a remarkable similarity between them and the rocks of the Hawaiian group.[1] The types already found in Savaii and in the neighboring islands include: olivine basalt, olivine-poor basalt, andesitic basalt, trachydolerite, "Alkalitrachyt," trachyte, and phonolite. "Savaii" is said to be the Samoan equivalent of the name "Hawaii." By a curious coincidence the vent of Matavanu is, among vents now active, the most perfect known analogue to Kilauea; and the volcanic mechanism seems to be practically identical in these two archipelagoes. The writer entirely agrees with Weber as to the necessity of regarding the subalkaline and alkaline rocks of each island group as syngenetic. The parallelism in the magmatic histories of Savaii and Hawaii is shown even in details, for Weber described olivine-augite nodules in the feldspar basalt of Mauga Loa, a rock which in all respects recalls the nodule-bearing, andesitic basalt of Mauna Kea.

Among the leading effusive types in Tahiti are olivine basalt, olivine-free basalt, haüynophyre, phonolite, and picrite, the description of the last-mentioned rock resembling that of the analyzed 1852 flow in Hawaii. Although basalts compose most of Tahiti, this mid-Pacific island has also furnished nephelite syenites, theralites, essexitic gabbros, and tinguaites.[2] In the Solomon islands olivine basalt and augite andesite are associated with an

[1] M. Weber, *Abhandlungen Math-phys. Klasse, Kgl. Bayerischen Akademie der Wissenschaften*, XXIV (1909), 287.

[2] A. Lacroix, *Bulletin Société géologique France*, X (1910), 91–124.

augite trachyte which is suggestively like the phonolitic trachyte of Puu Anahulu in Hawaii.[1]

Reconnaissances in Kerguelen Island show the intimate association of olivine basalt, basalt bearing olivine nodules, trachyte, and phonolite. Basalts and alkaline trachytes are the known species composing Ascension Island. St. Helena shows dominant olivine basalt and olivine-free basalt, with haüynite basalt and phonolite.

Without citing other parallels among the oceanic islands, it is now clear that the repeated association of volcanic species, ranging from olivine basalt to phonolitic trachyte or true phonolite, is not accidental. In all essential respects the argument for the gravitative differentiation of the salic types from normal basalt seems as strong for the chief Samoan island as it is for the chief Hawaiian island. It is commonly assumed that the subalkaline basalt and the alkaline phonolite originate in separate primary magma chambers. That hypothesis becomes almost, if not quite, incredible to any unprejudiced observer of the imposing likeness in the evolution of these distant, deep-sea island groups.

SUMMARY AND CONCLUSIONS

The writer's 1909 traverses in Hawaii have led to the view that the average of the many extant, typical analyses of its basalts approximates very closely the composition of the real average of all the basalt exposed in the island. This average is almost identical with that calculated for the world's average basalt. While Mauna Loa and Hualalai are basaltic from base to summit, Mauna Kea is, in a sense, stratified. Up to about the 6,000-foot contour, the broad basal slopes of Mauna Kea are underlain by the normal olivine basalt. From that contour to the summit platform, about 6,000 feet higher, the dominant lava is a basalt, very poor in olivine and, in other respects also, approaching the composition of a basic augite andesite. At the top of the mountain are flows and cinder-cones largely consisting of a still less femic type, in which alkaline feldspar (orthoclase or soda-

[1] W. W. Watts, *Geological Magazine*, XXIII (1896), 358.

orthoclase) seems often to form an essential constituent. This type is best classed as a trachydolerite of basaltic affinities. Its chemical analysis is almost identical with that of a common phase of the andesitic basalt, but, for some reason, alkaline feldspar did not crystallize from the latter magma. This arrangement of rock-species in Mauna Kea is explained as due to gravitative differentiation in the normal basaltic magma.

More pronounced splitting is registered in the highly alkaline trachydolerites and phonolitic trachyte occurring in the Kohala district and at Puu Anahulu and the neighboring Puu Waawaa. The development of these extreme types is tentatively ascribed to changes in the normal basalt by its solution of small quantities of sedimentary limestone cut by the respective lava conduits. No direct evidence for this hypothesis has been found; it is based on facts derived from the field and chemical relations of alkaline rocks throughout the world. Whether this hypothesis is correct or not, there can be little doubt that the alkaline rocks of Hawaii, Savaii, and other islands are as truly connected in a genetic way with the normal basalt, as ordinary aplite dikes are genetically connected with their respective granite batholiths. Such an origin for the Hawaiian alkaline rocks is rendered all the more probable because of their small relative bulk, and because of the perfect chemical transition which can now be shown between the normal basalt and the most salic of the alkaline types.

Further, a study of the olivine-pyroxene-anorthite segregations in the andesitic basalt and in the trachydolerite of Mauna Kea actually illustrates a stage of the differentiation. These nodules formed in the magma when its viscosity must have been enormous; else they would have rushed down into the conduit to levels where no summit eruption, of the small size represented in the flows and cones at the top of Mauna Kea, could have brought the nodules up again. It is almost certain that the settling-out of the olivine and pyroxene material (in solid or liquid phases) must have taken place at slightly higher temperatures, when the viscosity was much less. The residual magma must obviously become more alkaline in proportion to the degree of settling-out.

The ultra-femic material, sinking to great depth, where it

mixes with the hot, normal basalt, is subject to extrusion through lateral fissures which bring the deeper levels of the conduit into communication with the surface. Such is the preferred explanation for the ultra-femic olivine-basalt which emanated from Mauna Loa in 1852, and for the wehrlitic porphyry composing the Uwekahuna laccolith.

An explanation is offered for the apparently contradictory fact that gravitative differentiation is little evident in the thoroughly basaltic summit rocks of Mauna Loa and Hulalai, or in the material of the active vent at Kilauea.

As a result of studies in this and other fields, and in the general literature of petrology, the writer is inclined to the belief that all late pre-Cambrian and younger "alkaline" rocks are the result of differentiation within primary basaltic magma or within syntectic magmas formed by the solution of solid, generally sedimentary, rock in the primary basalt. The marvelously uniform composition of the basaltic magma issuing from countless fissures in every ocean basin as in every continental plateau, seems capable of explanation only on the premise that it forms the material of a continuous, world-circling substratum. The facts of geology suggest that this substratum was formed by an ancient liquation which took place when the globe was molten at its surface. This general conception became gradually clear to the writer during the genetic study of many intrusive bodies; it had been visualized in much the same form by that extraordinarily suggestive observer of the Hawaiian volcanoes, W. L. Green, whose *Vestiges of the Molten Globe*, Part II, first became known to the present writer in 1909. Not a single one of the myriad facts recorded in general petrography and geology definitely opposes this hypothesis, which, to the writer, seems to be the best working premise for a general philosophy of the igneous rocks.

Lastly, it appears from the accumulating results of geological work that the division of igneous rocks into "Atlantic" and "Pacific" races or groups is not warranted by the facts of distribution, nor by the requirements of sound petrogenic theory, nor by the needs of systematic petrography. In the heart of the Pacific basin, as in many regions along its borders, rocks of foyaitic,

theralitic, or other alkaline habit are already known, and the number of occurrences in that part of the earth is constantly growing. It may be quite true that alkaline rocks are more abundant on the Atlantic side of the globe—possibly because thick prisms of calcareous sediments are, in proportion to area, more developed in the Atlantic region—but it is yet more apparent that the overwhelming mass of the igneous rocks in the Atlantic region are subalkaline in type. The distinction of the two "Atlantic and Pacific races" (Sippen) is not only fallacious in the literal, geographic sense; it introduces an unnecessary pair of terms of quite elusive definition in place of the well-established, less nebulous terms "alkaline" and "subalkaline." The proved difficulty of making a clean-cut definition of the expression "alkaline rock" finds explanation in the theory that all late pre-Cambrian and younger alkaline rocks are of secondary origin, because derived from basalt or from its syntectics. According to this view, many transitional types should be found between the highly alkaline species and those low in alkalies; iron-clad definition becomes impossible.

PETROGRAPHIC TERMS FOR FIELD USE

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Velut aegri somnia, vanae
Finguntur species, ut nec pes nec caput uni
Reddatur formae.

—Horace, *De arte poetica*, 7.

Horace wrote this stanza with no idea of how aptly it would apply to the megascopic classifications of rocks in use at the beginning of the twentieth century. When the estimable authors of the Quantitative System appended a field classification to their system, they recognized the impossibility of accurately determining rocks megascopically, and said:

> It is obvious that a considerable part of the system of classification and nomenclature here proposed can only be applied upon microscopical or chemical investigation. . . . . For these reasons . . . . we are convinced of the need of general petrographical terms, which will be serviceable in the field work of the petrologist, and which will be of use to the general geologist and to those who may not be able to carry on microscopical and chemical investigations.

The authors proposed to select, from the terms originally given by the geologists of the past, certain rock names and to give to them their original significance "so far as possible, with only such modifications as a somewhat more systematic treatment of the matter may suggest." The suggestion was truly commendable, for the need of a field classification was seriously felt. Unfortunately, perhaps, we are not living in the old days. The former rock terms have, in the course of time, acquired new meanings, and an attempt to revive the old ones produces much confusion.

Ut sylvae foliis pronos mutantur in annos,
Prima cadunt; ita verborum vetus interit aetas,
Et juvenum ritu florent modo nata vigentque.

—Horace, *op. cit.*, 60.

And so it is with the old petrographic terms.

So far as the grouping of the rocks proposed by C. I. P. W. is concerned, it is most admirable, and can hardly be improved upon; it is only upon the rock terms chosen by them that any criticism falls. Teaching the names as selected, it is necessary to impress upon the student that these are only indefinite field terms—and he immediately wants to know the more exact definitions. The student who later takes up microscopical work finds —at the present time when the older systems must still be taught, even if supplementary to the newer—that these definitions produce confusion, and he must either "unlearn" the field terms or else originally he must have learned the more exact usage as well. The objection to the latter method is that it makes double work for those students who want only a general megascopic knowledge of the rocks. Had some simple change been made by the authors of the Quantitative System, either in the words used or in their endings, this difficulty would have been overcome. The following substitutes are proposed as expressing, more or less, the fact that the general type of rock represented by the original name is the one preponderating in the group, and for this reason the suffix *-eid* (from εἶδος, "form, appearance") was chosen. As a matter of fact the change proposed is not so great as the spelling would suggest. It is only a change in the ***pronunciation*** produced by the substitution of a single letter—from granite to granide, syenite to syenide, etc. The object in using *-eid* instead of *-ide* is twofold. It conforms to the derivation of the word, and in those countries where the final *e* is omitted, the ending *ide*, changed to *id*, has the short sound; *-eid* is everywhere pronounced the same. It will be noted that some of the C. I. P. W. terms are retained, for to such words as phanerite and aphanite there are no objections. For uniformity, however, the same ending is used below in these forms as in the others.

As divided by the authors of the Quantitative System, so here also the rocks are divided into three main divisions.

I. *Phanereids* (φανερος, "visible," and εἶδος, "form"). Rocks whose different constituents can be seen megascopically.

II. *Aphaneids* (αφανης, "unseen," and εἶδος). Rocks which contain a greater or lesser amount of megascopically indeterminable components. These are subdivided into

a) *Aphaneids*, properly so called. Non-porphyritic.

b) *Aphaneid porphyries*. Porphyritic rocks with aphanitic groundmasses. For consistency some other word should be substituted for porphyry, since this term is generally applied only to orthoclase rocks, and by some writers to rocks with two generations of minerals, with or without phenocrysts. The term, however, is in such general use among miners and quarrymen, and by the U.S. Geological Survey, for all rocks containing larger crystals in a fine-grained or dense ground-mass, that it may be better to retain it. Poikileid (ποικιλος, "spotted," and εἶδος) would be much better.

III. *Glasses*. Rocks which are hyaline or which have hyaline ground-masses.

On the basis of mineral composition, the rocks can be divided megascopically most easily into those that are light and those that are dark. Consequently the groups are divided into those in which

1. Femag[1] minerals form less than half the rock.
2. Femag minerals form over half the rock.
3. Light-colored minerals absent or nearly so.

While it is generally impossible to separate different feldspars megascopically, quartz can usually be recognized. Its presence or absence is therefore made the basis of a further subdivision, as is also the presence or absence of olivine in the no-feldspar rocks.

It has been found possible to subdivide the rocks megascopically into the following groups:

I. PHANEREIDS

Granoid.—A holocrystalline, medium- to coarse-grained igneous rock, consisting of quartz and any kind of feldspar, with one or more members of the biopyribole group,[2] generally biotite or hornblende. The femag minerals form less than 50 per cent of

[1] The term *femic* has been used repeatedly by recent writers as synonymous with ferro-magnesian. This is incorrect, since femic minerals include apatite, fluorite, calcite, etc. The term *femag* is here used for ferro-magnesian.

[2] *Biopyribole* is suggested as a substitute for the awkward words biotite $\left\{\begin{matrix}\text{and}\\\text{or}\end{matrix}\right.$ pyroxene $\left\{\begin{matrix}\text{and}\\\text{or}\end{matrix}\right.$ amphibole, and *pyribole* for pyroxene $\left\{\begin{matrix}\text{and}\\\text{or}\end{matrix}\right.$ amphibole.

the rock. Under this term are included all granites, and the light-colored quartz diorites.

Syeneid.—A holocrystalline, medium- to coarse-grained igneous rock, consisting of one or more kinds of feldspar and one or more members of the biopyribole group, generally biotite or hornblende. The femag minerals form less than 50 per cent of the rock. Under this term are included syenites, nephelite syenites, and the light-colored diorites.

There is a slight objection to this term in that the pronunciation is the same as cyanide. Sinai-eid (the rock at Sinai being a true syenite) might be used except for the superabundance of vowels. Esseneid or Assuaneid, from the modern names for Syene, are also suggested, but on the whole, on account of the common use of the term syenite, it seems best to retain syeneid.

Dioreid.—A holocrystalline, medium- to coarse-grained igneous rock in which the femag mineral is an amphibole and forms over half the constituents. Feldspar, of any kind, is subordinate in amount. To this group belong the shonkinites, the dark-colored diorites, and the hornblende gabbros.

Quartz dioreid is a subgroup.

Gabbreid.—A holocrystalline, medium- to coarse-grained igneous rock in which the femag mineral is pyroxene and forms over 50 per cent. Feldspar, of any kind, is subordinate in amount. Here are included the augite diorites, gabbros, and norites.

Quartz gabbreid is a subgroup.

Dolereid.—It is usually impossible to determine, megascopically, the species of pyribole present. In such cases the term dolereid may be used instead of dioreid or gabbreid.

Quartz dolereid is a subgroup.

Pyroxeneid.—A holocrystalline, medium- to coarse-grained igneous rock which consists almost entirely of pyroxene. The term covers the rocks now called pyroxenites.

Amphiboleid.—A holocrystalline, medium- to coarse-grained igneous rock which consists almost entirely of amphibole. It includes igneous hornblende rocks, whether the hornblende is primary or secondary.

Pyriboleid.—A holocrystalline, medium- to coarse-grained ig-

neous rock, consisting almost entirely of one or more members of the pyribole group. It includes the pyroxeneids and amphiboleids, and corresponds to dolereid among the feldspar rocks.

Peridoteid.—A holocrystalline, medium- to coarse-grained igneous rock, consisting of olivine, with or without pyriboles. Feldspar is absent. This group includes the peridotites.

II. APHANEIDS

Felseid.—An aphanitic igneous rock, non-porphyritic and light-colored. Here are included non-porphyritic rhyolites, trachytes, phonolites, latites, and the light-colored andesites. They are *leuco-aphaneids* (λευκος, "white").

Felseid porphyry.—Under this head are grouped all light-colored porphyritic igneous rocks with aphanitic ground-masses. They may also be called *leucophyreids.*

Quartz felseid porphyries or quartz leucophyreids are those felseid porphyries among whose phenocrysts quartz can be recognized. Other mineral modifiers, such as orthoclase, biotite, hornblende, etc., may be used for different varieties.

Anameseid.—An aphanitic igneous rock, non-porphyritic and dark colored, generally dark gray, dark green, dark brown, or black. In this group are included the dark andesites and basalts. They are *melano-aphaneids* (μελανος, "dark").

No sharp line can be drawn between these rocks and the felseids. The relative amounts of the dark and the light constituents cannot be determined megascopically, and it is only possible to classify the felseids by their colors, which are white, yellow, light brown, pink, and pale gray.

Basalt, being such an overworked word, von Leonhard's term anamesite was chosen instead as the root. It was originally applied to basaltic rocks of such fine texture that the constituents were indistinguishable megascopically.

Anameseid porphyry.—In this group belong all dark-colored porphyritic igneous rocks with aphanitic ground-masses. The term *melanophyreid* may also be used. If the phenocrysts can be determined, their names may be prefixed, as biotite melanophyreid or biotite anameseid porphyry, etc.

III. GLASSES

Since the glasses can be determined megascopically as such, the usual terms are retained, as pumice, obsidian, pitchstone, etc. For the porphyritic glasses the term *vitrophyreids* is proposed.

Tabulating these terms:

	Femag Minerals <50 per cent		Femag Minerals >50 per cent		No Feldspar or Quartz	
	+Quartz	−Quartz	− Quartz	−Quartz	−Olivine	+Olivine
Usual femag	Biotite	Biotite, Amphibole	Amphibole	Pyroxene	Pyribole	Olivine, Pyribole
Glasses	Pumice, obsidian, pitchstone, etc.					
Porphyritic glasses	Vitrophyreids					
Aphaneids	Felseid		Anameseid			
Aphaneid porphyries	Felseid-porphyry or leucophyreid		Anameseid porphyry or melanophyreid			
Phanereids	Graneid	Syeneid	Dioreid	Gabbreid	Amphiboleid Pyroxeneid	Peridoteid
			Dolereid		Pyriboleid	

Such a classification can be learned by a student in ten minutes. The rocks are subdivided into as many groups as can be recognized megascopically, and unknown specimens classified by different persons will almost invariably be found to fall into the same groups. Frankly acknowledging, by the names used, the field character of the determinations, there will be no confusion caused if later more exact terms are applied to the same rocks.

THE EVOLUTION OF LIMESTONE AND DOLOMITE. I

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INTRODUCTION

Many writers[1] have called attention to the decrease in the percentage of dolomite in going up the geologic time scale, and

[1] Daly has shown the decrease in dolomite with age in the following compilation of analyses (Table I, from *Bull. Geol. Soc. Am.*, XX, 165):

TABLE I

AVERAGE RATIO OF CALCIUM TO MAGNESIUM IN LIMESTONES OF DIFFERENT PERIODS

Period	1 Number of Analyses	2 Ratio of $CaCO_3$ to $MgCO_3$	3 Ratio of Ca to Mg
Pre-Cambrian:			
a) From North America, except those in *b*)	28	1.64:1	2.30:1
b) From Ontario (Miller)	33	4.92:1	6.89:1
c) Average of *a*) and *b*)	61	2.93:1	4.10:1
d) Best general average	49	2.58:1	3.61:1
Cambrian (including 17 of the Shenandoah limestone)	30	2.96:1	4.14:1
Ordovician	93	2.72:1	3.81:1
Silurian	208	2.09:1	2.93:1
All pre-Devonian	392	2.39:1	3.35:1
Devonian	106	4.49:1	6.29:1
Carboniferous	238	8.89:1	12.45:1
Cretaceous	77	40.23:1	56.32:1
Tertiary	26	37.92:1	53.09:1
Quaternary and Recent	26	25.00:1	35.00:1
Total	865		

various hypotheses have been offered for its explanation. Probably the majority of geologists hold that it is due to a secondary alteration of limestone to dolomite, which is roughly proportional to time. Daly[1] has suggested that it is due to a change in the nature of the life processes which effect the precipitation of carbonates in the sea. Still another alternative hypothesis is herewith offered, that the percentage of dolomite developed in the sea has declined with time, and that this was controlled by a progressive increase in the ratio of calcium to magnesium contributed from the lands.

Absolute proof for any one of these hypotheses is impossible from the very nature of the problem. For instance, all of them are based on the theory of uniformitarianism, a theory deep rooted in geologic evidence, but a theory nevertheless. All the hypotheses offered involve the question of whether dolomite develops predominantly in the sea, regardless of the specific processes of formation, or whether it is predominantly a secondary product from limestones, after their emergence from the sea. If its origin is mainly in the sea, which of the factors controlling deposition in the sea has changed so as to cause a decline in its deposition with time? Was it temperature, pressure, life processes, the chemical composition of the sea, or some combination of these factors? To these no final answer can be made. The available evidence for each view can be sifted. Conclusions may be drawn, but the probability may be freely recognized that in the future some of the conclusions may become invalidated.

PART I. THE EVIDENCE ON THE ORIGIN OF DOLOMITE

That the predominance of dolomite in the ancient sediments is due in a larger measure to primary conditions of deposition in the sea than to the metamorphism of limestones after their emergence from the sea seems to follow from a comparison of the evidence on the origin of dolomite in the sea with that on the origin of dolomite by the metamorphism of limestone after its emergence from the sea.

A. THE EVIDENCE FOR THE ORIGIN OF DOLOMITE IN THE SEA

Interstratification of limestones, magnesian limestones, and dolomites the result of primary conditions of sedimentation, or of the

[1] *Ibid.*

differential metamorphism of limestones after their emergence from the sea.—In a succession of conformable formations, each formation usually presents a certain specific lithologic unity of character which is different from that of adjacent formations, and may or may not be related to them by gradation phases. Thus limestones are not infrequently sharply interstratified with dolomites, and give by their color contrasts a graphic portrayal of the sharp lithologic difference which frequently distinguishes adjacent carbonate formations. Attention is directed to a number of typical illustrations of sharply defined stratigraphic cleavage between limestones and dolomites. The "lead and zinc" district of southwestern Wisconsin presents the following interesting succession:

System	Formation	Average Thickness in Feet	Lithological Character, etc.
	Hudson River	160	Shale.
	Galena	250	Dolomite. Limestone layers, sharply interstratified near bottom.
	Containing oil rock	3±	Oily shale, not deposited everywhere.
Ordovician			
	Clay	3±	Not deposited everywhere.
	Glassrock	3±	Sharply defined limestone. Very pure.
	Platteville	55	Magnesian limestone and dolomite.

A striking case of sharp interstratification of nearly pure limestone beds and dolomites is described by F. B. Peck[1] as occurring in the Trenton of Lehigh and Northhampton counties, Pa.

I. P. Lesley's[2] study of the Cambro-Silurian limestones of Cumberland County, Pennsylvania, is perhaps the most detailed quantitative chemical study of a limestone section which has ever been made from the viewpoint of throwing light on the origin of limestone and dolomite. The section studied was about 375 feet

[1] F. B. Peck, *Eco. Geol.*, III, No. 1, p. 43.

[2] I. P. Lesley, *Second Geol. Survey Pa.*, Vol. MM (1897), pp. 311–62.

thick, consisting of conformable, uniformly dense, slightly disturbed beds of limestone sharply interstratified with beds of magnesian limestone and dolomite. Analyses taken from various parts of each bed showed that each bed constituted a lithologic unit which often differed sharply from adjacent beds.

To E. Suess,[1] the sharply defined, thin-bedded intercalations of limestone and dolomite in the Plattenkalk present such powerful evidence of characters which could not have been acquired by metamorphism after their emergence from the sea, that he regards them as direct chemical precipitates. While it may be difficult to agree with Suess that chemical precipitation, in cases like that of the Plattenkalk, is proven, there certainly can be no doubt that it is easier to conceive of such formations as being the direct result of sedimentary processes in the sea, than to believe them to be the result of the differential metamorphism of limestone beds after their emergence from the sea. It is difficult to see how the metamorphism of a succession of conformable limestone beds or formations after their emergence from the sea could be so thoroughly selective as to result in a succession of beds or formations of unlike composition. Circulating underground water, the most universal agent of the alternation of sediments after their emergence from the sea, is obviously most effective along joints, bedding planes, or other large openings both parallel to and across the bedding, the so-called "trunk channels of circulation" repeatedly emphasized by Van Hise in his" Treatise on Metamorphism."

Until more direct evidence has been submitted for the origin of dolomite formations through circulating underground water, it seems more reasonable to assume that interstratifications of dolomite and limestone result from primary conditions of sedimentation, regardless of what the specific processes of limestone and dolomite building may have been.

Fineness of grain, peculiar to some dolomites, probably indicative of very little metamorphism since deposition.—Attention is directed to the fineness of grain which some dolomites possess. Daly[2]

[1] E. Suess, *The Face of the Earth*, II, 262.

[2] R. A. Daly, "The Evolution of the Limestones," *Bull. Geol. Soc. of America*, XX (1909), 167–68.

finds that the slightly disturbed dolomites of Cambrian and pre-Cambrian age of the forty-ninth parallel section of the Rocky Mountain geosynclinal, aggregating about 7,000 feet in thickness, are singularly monotonous in their fineness of grain, averaging about 0.02 millimeter. Other fine-grained and similarly undisturbed dolomites mentioned by Daly are those of the Archean at the headwaters of the Priest River, Idaho, the magnesian limestones and dolomites inclosing the chitinous fossil Beltina donai in the Clarke range and the Siyeh and Sheppard siliceous limestones of northwestern Montana, probably of middle Cambrian age. He also quotes Vogt as stating that the finest grained Norwegian dolomites average from 0.02 to 0.03 millimeter in diameter.

Willis and Blackwelder in their studies of the geology of China for the Carnegie Institution describe a number of very fine-grained, dense dolomites of considerable extent and thickness.

The pre-Cambrian dolomite formation of the Baraboo[1] synclinal is singularly fine grained. The Niagara limestone of Wisconsin, a dolomitic formation, is generally a very even-textured, fine-grained, and compact rock.

The generalization may be deduced from the facts cited that many undisturbed or only slightly disturbed dolomites are exceedingly fine grained and compact. There does not appear to be any evidence that this fineness of grain is the result of granulation. Furthermore, the relative mobility and regenerative power of the carbonates is very great as compared with the other minerals. Coarse-grained, even-textured[2] marbles showing no strain effects are found interbedded with banded gneisses with marked strain effects. Unless conditions are peculiarly unfavorable for recrystallization, the metamorphism of dolomites would probably result in coarser grain. The fineness of grain and compactness of many dolomites may therefore be interpreted as showing that they were dolomite before they emerged from the sea.

Many dolomite formations lack fossils.—The opinion is reflected from geologic literature that fossils are less common in dolomite

[1] S. Weidman, "Baraboo Iron-bearing District," *Wisconsin Survey Bull.*, No. 13 (1904), p. 67.

[2] C. R. Van Hise, "Treatise on Metamorphism," *U.S.G.S. Mon. 47*, p. 738.

than in limestone, although no quantitative study of this problem seems to have been made. It has been observed in various places that the limestone beds intercalated between dolomite are full of fossils, while the dolomite is barren. Illustrations of this are found in the Galena limestone of Wisconsin. The paucity of fossils in dolomites has been variously interpreted, some holding that fossils were never present in the formation because the conditions at the time of deposition were unfavorable to life, while others claim that they were originally present but have been destroyed by metamorphism. In connection with the first interpretation, it is interesting to note that magnesium-bearing solutions have actually been found to be unfavorable to life processes. It may be the correct interpretation in the case of certain dense, fine-grained dolomites. On the other hand, porous, cavernous dolomites like the Lower Magnesian of the Upper Mississippi valley, which is nearly devoid of fossils, evidently has undergone considerable recrystallization which may have destroyed the fossil record. No final conclusion seems to follow from the apparent fossil barrenness of dolomites with reference to the origin of dolomite.

Association of certain dolomites with gypsum and salt deposits.—Of certain dolomites which are found with deposits of salt, gypsum, and red beds and other indications of aridity and concentrated seas, it has been suggested that they are direct chemical precipitates, since conditions of deposition were apparently unfavorable to life. This view is open to the criticism that no case is known where this process is in operation at the present time. However, regardless of what the specific processes of dolomite building were, it seems more likely that these deposits were primarily dolomite because gypsum tends to decompose dolomite into calcium carbonate and magnesium sulphate. Therefore, if any alteration of the deposit had taken place since deposition, it would seem more likely to result in the decomposition of dolomite than in dolomitization.

Chemical precipitation of dolomite in the sea.—Crystals of dolomite grow in vugs and cavernous openings of coral reefs in the Pacific Ocean, according to E. W. Skeats.[1]

[1] E. W. Skeats, *Bull. Mus. Comp. Zoöl.*, XLII (1903), 53–126.

Experimental evidence for the chemical precipitation of dolomite.—The direct precipitation of dolomite from solution has apparently not been done, experimentally. Sterry Hunt[1] precipitated calcium carbonate and the hydrous carbonate of magnesium with sodium carbonate and found that he could develop dolomite by heating this mixture to 120° C.–130° C. Obviously this experiment did not accomplish direct chemical precipitation of dolomite nor is it applicable to the explanation of the majority of dolomites in nature.

Daly's hypothesis of the direct precipitation of dolomite in the primitive ocean.—Daly[2] postulates that dolomite was precipitated from a nearly limeless primitive ocean by ammonium carbonate generated by the decay of organisms on the bottom of the ocean. The hypothesis is based on several assumptions, namely: (*a*) the scavenging system of the pre-Cambrian and the early Paleozoic ocean was less perfect than at present; (*b*) the post-Huronian uplift gave a tremendous impetus to the transportation of lime to the sea, which in turn stimulated the development of lime-secreting organisms; (*c*) the improvement of the scavenging system and the development of lime-secreting organisms gradually brought the balance in favor of the deposition of limestones by organic secretions over direct chemical precipitation. The theory is offered to explain a number of facts: (*a*) the predominance of dolomite in the older formations; (*b*) characteristics such as grain, fossil record, and field relations of certain dolomites indicative of direct chemical precipitation; and (*c*) the apparent similarity between the ratio of calcium to magnesium in the older dolomites and the ratio of calcium to magnesium of streams on pre-Cambrian crystalline terranes. This theory fits many facts remarkably well. However, the premises on which it is based are open to objection.

It is true that the decay of marine organisms generates[3] ammonium carbonate and other precipitants. But organic decay also generates carbonic acid, which tends to keep the carbonates of

[1] Sterry Hunt, *Chem. and Geol. Essays* (1895), 80.

[2] R. A. Daly, "First Calcareous Fossils and the Evolution of the Limestones," *Bull. Geol. Soc. of America*, XX, 153–70.

[3] G. Steinmann, *Ber. Naturforsch. Gesell. Freiburg*, IV (1889), 288; Challenger, *Report on Deep Seas*, 255.

lime and magnesia in solution. The rapid corrosion of marine shells is partly ascribed to this agency, by the authors of the Challenger deep-sea report. Thomson's[1] observations that the local abundance of carbonic acid on the ocean bottom is associated with an abundance of organisms is suggestive. Corrosion of calcareous remains by the direct action of sea water, but predominantly by the action of carbonic acid resulting from organic decay, is regarded by Murray as sufficiently powerful to prevent the accumulation of calcareous ooze at a mean depth of 2,730 fathoms, over 51,500,000 square miles of ocean bottom, the Red Clay area.

It therefore seems to be an open question whether the net chemical effect resulting from organic decay in the ocean is precipitation or corrosion. The scavengers of the present ocean do not arrest the accumulation of calcareous oozes over millions of square miles of the ocean bottom. The evidence that direct precipitation of calcium carbonate is taking place on those vast areas of organic decay is doubtful. Philippi,[2] viewing direct chemical precipitation as an important process in the origin of limestones, after citing the data offered by various investigators for direct chemical precipitation from the present ocean, concludes that certain incrustations and the cements of some oozes are probably chemical precipitates. He believes that warm seas, teeming with life, where decay on the bottom is rapid are favorable localities for the precipitation of calcium carbonate.

The acquisition of the lime-secreting habit by marine organisms in response to an accumulation of lime in the ocean postulated as a result of the post-Huronian erosion cycle, and the increase in scavengers may be possible. Paleontologists believe that at least nine-tenths of the organic evolution into main stocks was accomplished before the Cambrian. The Cambrian record contains evidence for the existence of all phyla excepting the vertebrates, and the unsuccessful search for vertebrate fossils in the Cambrian cannot be regarded as conclusive evidence for their absence. The burden of proof, therefore, rests heavily on any theory based on

[1] C. Wyville Thomson, *Depths of the Sea*, 502–11.

[2] Philippi, *Neues Jahrb.* (1907), 444.

radical differences in the organic development of the early Paleozoic, as compared with the present, and a correlative, fundamental difference in the constitution of the ocean.

Nor would all students of the pre-Cambrian admit that the profound importance which Daly attaches to the post-Huronian erosion cycle is evident. It was preceded by at least three periods of emergence in the Lake Superior and Lake Huron regions and in Finland. So far as known, any one of them may have contributed as much lime to the sea as the post-Huronian.

Deposition of magnesian limestones by marine organisms.—Marine organisms deposit magnesium carbonates in small quantities. According to G. Forchhammer,[1] marine shells and corals contain magnesium carbonate in varying amounts from 0.15 to 7.64 per cent, 1 per cent being rather above the average. In *Lithothamnium nodosum*, Gümbel[2] found 2.66 per cent of magnesium and 47.14 per cent lime, and Högbom[3] in fourteen analyses of algae belonging to this genus reports from 1.95 to 13.19 per cent of magnesium carbonate.

The development of magnesium limestones and dolomites by marine leaching.—It has been shown that marine leaching is very effective in concentrating the magnesian content of limestone formations. This is due to the fact that calcium carbonate is several times as soluble as magnesium carbonate, as was first shown by Bischoff. The decrease in calcium carbonate and the corresponding increase in magnesium carbonate resulting from marine leaching is well shown in the table on p. 333, compiled by G. Högbom.[4]

Högbom[5] washed the clay marl of Upsula with carbonated water with the following results. The original composition of the marl was calcium carbonate, 18 per cent, magnesium carbonate, 1.3 per cent. The loss of calcium carbonate was about 50 per cent, while the loss of magnesium carbonate amounted to only a trace.

In his studies of the marine marls of Sweden, Högbom found

[1] G. Forchhammer, *Neues Jahrb.* (1852), 854.

[2] Quoted from *Bull. 330, U.S.G.S.*, 485.

[3] Högbom, *Neues Jahrb.* I (1894), 262.

[4] *Ibid.*, 262–74.

[5] *Ibid.*, 268.

that the transported material contained progressively larger proportions of magnesium as its distance from the parent limestone increased. Near its point of origin, the marl carried 3.7 parts of magnesium carbonate to 100 of calcium carbonate, and from these figures the ratio was generally raised to 36 magnesium carbonate and 100 calcium carbonate.

TABLE II

TABLE COMPUTED FROM 21 GLOBERGERINA, 21 RED MUDS, 7 RADIOLARIAN OOZES, PTEROPOD OOZE, DIATOM OOZE, AND BLUE MUD

$CaCO_3$ Limits	$CaCO_3$	$MgCO_3$	Relative Values*	Analysis
80–100.....	86.7	17	.8	8
60–80.....	68.3	1.4	2.0	8
40–60.....	52.	1.2	2.4	8
20–40.....	32.	.9	3.0	3
10–20.....	16.2	1.6	10.0	4
5–10.....	6.1	.7	11.5	1
3–5.....	3.7	1.6	43.0	7
1–3.....	2.0	2.1	105.0	9

* Relative values express parts of $MgCO_3$: 100 parts of $CaCO_3$.

The stalactites from the caverns in the coral rocks of Bermuda, according to Högbom, contain only 0.18 to 0.68 per cent of magnesium carbonate, while the rocks themselves carry about five times as much magnesium carbonate. The lime salt has evidently dissolved much more freely than the magnesium compound. This mode of concentrating magnesium carbonate must, from the evidence cited, be regarded as real, and may be instrumental in causing the development of dolomite. It is obvious that the smaller the content of calcium in the sea, as compared with magnesium, that is, the smaller the relative quantity of calcium resulting from the difference between contribution from the land on the one hand, and precipitation on the other, the more effective will be the process of leaching. The precipitation of calcium carbonate in the sea is now largely controlled by life processes, and probably has been at least as far back as the beginning of the Paleozoic, so that since Zoic times there has been a powerful agency at work, tending to deplete the calcium content of the sea, while leaving the soluble magnesium salts to accumulate. Solid phases of calcium carbonate are therefore farther removed from a condition

of equilibrium with sea water than the corresponding magnesium salt. Aside, then, from the inherent difference between the solubility of calcium carbonate and magnesium carbonate, the chemistry of the sea apparently facilitates the solution of calcium carbonate and retards that of magnesium carbonate. Assuming that the efficiency of the organic precipitation of calcium carbonate has been about the same throughout Zoic times, it seems obvious that the concentration of magnesium carbonate in calcareous deposits by marine leaching would have been even more effective than now, if at some time in the past the rivers had contributed relatively less lime and more magnesia than at present. If there is any probability that such has actually been the case, that would constitute one factor which would operate to cause an increase in the magnesium content of limestone in descending the geologic time scale.

The origin of dolomite by the secondary replacement of calcium by magnesium in the sea.—Coral rocks originally contain only a small percentage of magnesium carbonate, usually less than 1 per cent. In 1843, J. D. Dana[1] in a rock from the coral island of Makatea, in the Pacific, reported magnesium carbonate to the extent of 38.07 per cent. This approached the dolomite ratio which requires 45.7 per cent, and it was suggested that the rock had been dolomitized through secondary replacement, the magnesium carbonate probably having been derived from the concentration of shallow lagoons of sea water. Since Dana's time, many other investigators have recorded similar enrichments of coral reefs. In a coral reef from Porta do Mangue, Brazil, T. C. Branner[2] reports 6.95 per cent of magnesia, equivalent to 14.6 of carbonate, while the corals themselves contained only 0.20 to 0.99 per cent of magnesia. E. W. Skeats[3] reports analyses of dolomitic coral rock of the Pacific in which the magnesium carbonate rises to a maximum of 43.3 per cent.

The borings from the atoll of Funafuti as discussed by J. W. Judd[4] present a remarkable case of transformation from reef

[1] J. D. Dana, *Corals and Coral Islands* (3d ed.), 393.

[2] T. C. Branner, *Bull. Mus. Comp. Zoöl.*, XLIV (1904), 264.

[3] E. W. Skeats, *Bull. Mus. Comp. Zoöl.*, XLII (1902), 53–126.

[4] J. W. Judd, *The Atoll of Funafuti*, quoted from *Bull. 330, U.S.G.S.*, 487.

rock to dolomitic limestone. The principal boring was driven to a depth of 1,100 feet, through coral and coral rock all the way, and samples of the cores were analyzed every ten feet of the distance. The following table of data, quoted by *Bull. 330, U.S.G.S.*, p. 487, shows first, an enrichment in magnesium carbonate near the surface, then an irregular rising and falling in much smaller amounts, while below 700 feet the rock approaches the dolomite ratio.

TABLE III

MAGNESIUM CARBONATE IN BORINGS ON ATOLL OF FUNAFUTI

Depth Feet	Percentage $MgCO_3$	Depth Feet	Percentage Magnesium Carbonate
4	4.23	295	3.6
13	7.62	400	3.1
15	16.40	500	2.7
20	11.99	598	1.06
26	16.0	640	26.33
55	5.85	698	40.04
110	2.11	795	38.92
159	0.79	898	39.99
200	2.70	1000	40.56
250	4.9	1114	41.05

In the analyses of coral rock borings from an artesian well at Key West, Florida, reported by George Steiger,[1] there is no apparent relation between the content of magnesia and depth as shown by the borings on the atoll of Funafuti.

TABLE IV

LIME AND MAGNESIA IN BORINGS AT KEY WEST

Depth Feet	Percentage CaO	Percentage MgO	Depth Feet	Percentage CaO	Percentage MgO
25	54.03	0.29	1325	54.49	0.62
100	54.01	0.77	1400	55.12	0.30
150	54.38	0.86	1475	54.48	0.73
350	51.46	1.67	1625	53.90	1.14
600	48.87	2.50	1850	54.28	1.12
775	46.53	6.70	2000	54.02	1.06
1125	53.84	0.86			

The dolomitization of organic calcareous deposits in the sea by secondary replacement as well as by leaching seems to be too well established to admit of serious doubt. The degree of dolo-

[1] George Steiger, *Bull. 228, U.S.G.S.* (1904), 309.

mitization in any given case may be influenced slightly by the original composition of the calcareous secretions: witness the difference in the content of magnesium carbonate in secretions from Lithothamnium and other members of this genus as compared with those of the corals. Certain calcareous secretions have been found to consist of calcite while others like those of the corals consist largely of aragonite. Aragonite is much less stable than calcite, hence the aragonite secretions are probably much more subject to dolomitization through leaching and replacement than the more stable form of calcium carbonate, calcite. Furthermore, it is highly probable that the composition of the sea is an important factor in dolomitization. If sea water is high in magnesium and low in calcium, it is probable that the conditions are more favorable for the dolomitization of calcareous deposits than if the reverse condition prevailed, as may be inferred from the following experiments. If a crystal of calcite is placed in water, solution will take place until equilibrium is reached between the calcite and the solution. Obviously, replacement, in the absence of magnesium salts, cannot take place. On the other hand, Sorby found that a crystal of calcite placed in a concentrated solution of magnesium chloride became slowly incrusted with magnesium carbonate, and Pfaff developed a dolomitic material by subjecting calcium carbonate to the action of a solution of magnesium chloride or sulphate and common salt, under pressure comparable to the deep sea, in which case the speed of reaction was proportional to the concentration of the solution.

It is obvious that 60 pounds of calcium carbonate could not be replaced by a solution containing only 10 pounds of magnesium salt in anything like the proportions required by the dolomite ratio. It seems equally probable, a priori, that if the river waters carried calcium and magnesium to the sea in the ratio of 1:1, the chances for dolomitization through leaching, secondary replacement, or possibly primary deposition would be better, all other things being equal, than when the proportion of river-borne calcium to magnesium is 6:1, which is the approximate ratio at the present time according to the best estimate.[1]

[1] See F. W. Clarke, "A Preliminary Study of Chemical Denudation," *Smithsonian Mis. Coll.*, LVI, No. 5, p. 8.

Experimental evidence on the origin of dolomite by secondary replacement of calcium chloride.—A summary of the principal experimental methods by which the dolomitization of calcium carbonate by replacement has been effected follows:

1. REPLACEMENT AT HIGH TEMPERATURE

By heating calcium carbonate and a solution of magnesium sulphate in a closed tube at 200° C. (Morlot, *Jahresb. Chemie* [1847–48], 1290).

By heating carbonate of lime to over 100° C. with a solution of magnesium bicarbonate (F. Hoppe-Seyler, *Zeitsch. Deutsch. Geol. Gesell.*, XXVII [1875], 509).

By the action of a solution of magnesium chloride on calcium carbonate at high temperature (Marignac and Faber, *Compt. Rend.*, XXVIII [1849], 364).

By saturating chalk with a solution of magnesium chloride and heating the mass on a sand bath (Saint-Claire Deville, *Compt. Rend.*, XLVII [1858], 91).

By heating fragments of porous limestone with dry magnesium chloride in a gun barrel (J. Durocher, *Compt. Rend.*, XXXIII [1851], 64).

It is probable that the preceding experiments on the replacement of calcium carbonate have very little significance in relation to the development of dolomite in the sea, since the continuity of the life record back as far as the pre-Cambrian, at least, precludes the possibility of a universally hot ocean. Very locally, as in the case of the eruption of Krakatao, the required temperatures may have been duplicated in the ocean. They are more likely to have been paralleled in some cases of contact, metamorphism of limestones generally following their emergence from the sea.

2. REPLACEMENT ABOVE 60° C.

By action of magnesium sulphate on aragonite in a concentrated solution of common salt at a temperature above 60° C. (Klement, *Min. Pet. Mitth.*, XIV [1894], 526).

The same objection holds against the application of this experi-

ment of the development of dolomite in the sea as was urged against the preceding group of experiments. The highest temperatures of the sea, resulting from solar heating, on record are those of the Red Sea[1] (31° C.), and the Lagoons of the Celebes (32° C.).

3. FORMATION OF DOLOMITE AT ORDINARY TEMPERATURE AND PRESSURE

By action of magnesium chloride and magnesium sulphate in water on anhydrite in the presence of common salt and carbonic acid (Pfaff, Jr., *ibid.*, 557).

By action of hydrogen sulphide in water on magnesium and calcium carbonates, followed by the introduction of carbonic acid (Pfaff, Jr., *ibid.*, 556).

4. FORMATION OF DOLOMITE AT ORDINARY TEMPERATURE AND HIGH PRESSURE

By the action of sodium carbonate on anhydrite in the presence of common salt in a concentrated solution of magnesium sulphate or chloride (Pfaff, *ibid.*, 562).

By the action of magnesium chloride or sulphate in a solution of common salt on calcium carbonate. The speed of the reaction is proportional to the degree of concentration of the solution (Pfaff, *ibid.*, 565).

Pfaff's experiments are highly creditable in that the replacement of calcium carbonate by a magnesium salt so as to yield a product approaching the dolomite ratio was effected without resort to high temperatures. Doubtless other methods will yet be worked out whereby this result can be obtained under conditions similar to those prevailing in the sea. The last experiment by Pfaff is highly suggestive when compared with the increase in the magnesium content of marine oozes with depth; that is with pressure (see this paper, p. 335). However, it does not seem safe to argue that this has been a very important factor of control, since many dolomites have very obvious earmarks of shallow-water deposition, such as ripple marks, cross-bedding, and interstratification with coarse sands.

[1] Quoted by F. W. Pfaff, *Neues Jahrb. Min. Beilage*, XXIII (1907), 573.

B. THE EVIDENCES FOR THE ORIGIN OF DOLOMITE BY THE METAMORPHISM OF LIMESTONES AFTER THEIR EMERGENCE FROM THE SEA

Direct chemical precipitation of dolomite.—The occurrence of dolomite in veins and vugs of limestone and dolomite is well known. So far as the recorded facts seem to indicate, direct chemical precipitation of dolomite in fissures and openings of carbonate formations, after emergence from the sea, seems to be much more important than the chemical precipitation of dolomite in the sea at the present time. However, dolomite as a cement and vein filler is quantitatively of far less consequence than calcite. Furthermore, it is not certain to what extent dolomite in veins merely means the transfer of previous existing dolomite originally developed in the sea. Direct chemical precipitation of dolomite in formations after their emergence from the sea, while probably more important than the chemical precipitation of dolomite in the sea at the present time, is nevertheless a very subordinate process and cannot be regarded as an important source of dolomite formations.

Origin of dolomite by leaching limestones after their emergence from the sea.—The dolomitization of limestones after their emergence through leaching is a very important process wherever both the calcium carbonate and dolomite are originally present, because of the differential solubility of the two carbonates. Unquestionably a unit volume of water as it enters the soil, but charged with atmospheric gases, is a much more efficacious solvent than an equal volume of sea water, but the total volume of sea water which is effective in leaching carbonates in the sea is vastly greater than the volume of water in the lithosphere. Leaching of limestones by underground waters probably changes the ratio of calcium to magnesium but little excepting near the surface, because the porosity, slumping, and faulting which would need to follow from converting a magnesian limestone containing even 13 per cent of magnesium carbonate into a dolomite through leaching is not at all evident in dolomite formations. Evidence is cited showing that weathering does increase the percentage of magnesia in limestones. Since effective leaching of limestones by ground water is related to weathering, it is improbable that

this process accounts for the stratigraphic separation of limestones, magnesian limestones, and dolomites, or for any large proportion of the dolomite in nature.

Origin of dolomite by secondary replacement of limestone.—Secondary dolomitization along fissures had been described by Prestwich,[1] Geikie,[2] Bain,[3] Pfaff,[4] Spurr,[5] and others. The alteration of limestones by hot, magnesian spring waters at Aspen, Colorado, described by Spurr is significant, but obviously, secondary replacement by underground water seems to be only local. A brief consideration of the chemistry of ground water and of the ocean is suggestive in showing the probabilities for the relative replacing power of sea water and underground water. Sea water[5] contains calcium and magnesium in the ratio of 1 to 3.11. The salinity is 3.301 to 3.737, of which 1.197 per cent is calcium and 3.725 per cent magnesium. The constitution of underground water is variable and depends upon the local composition of the rocks from which it is taken. Underground water of terrestrial origin is nearly free from mineral matter at the start but contains solvent gases from the atmosphere. Obviously, if a unit volume of unmineralized underground water comes into contact with a unit weight of carbonate rock, solution follows until equilibrium is attained between the solid and liquid phases which are in contact. If the temperature, pressure, and the volume of water remain unchanged nothing further results. It is this history of the source of the salts in terrestrial underground waters which is unfavorable to replacement.

In humid regions, underground waters are essentially carbonate waters in which the principal positive ion is calcium. The following analysis may be taken as illustrative:

[1] Prestwich, *Geology—Chemical, Physical and Stratigraphical* (Oxford, 1886), I, 133–44.

[2] Geikie, *Textbook of Geology* (3d ed.; MacMillan, London, 1893), 321.

[3] Bain, "Preliminary Report on the Lead and Zinc Deposits of the Ozark Regions," *Twenty-second Ann. Rept. U.S. Geol. Survey*, Part II (1901), 208–10.

[4] Pfaff, *op. cit.*, XXIII (1907), 529–80.

[5] Spurr, "Geology of the Aspen Mining Dist., Colorado," *Mon. U.S. Geol. Survey*, XXXI (1898), 210–91.

[5] Mean of 77 analyses of ocean water from many localities collected by the Challenger expedition. Quoted from *Bull. 330, U.S. Geol. Survey*, 94.

COMPOSITION OF EXCELSIOR SPRINGS, MISSOURI[1]

SALINITY 489 PARTS PER MILLION OF WATER, OR ABOUT 0.4 PER CENT

Ca	29.28
Mg	3.15
Co_3	55.92

Ratio of Ca to Mg 9.3:1

The calcium carbonate of the ocean bottom is in contact with a solution high in magnesium and low in calcium, largely derived from the lands and not from the ocean bottom. The calcium carbonate of the land areas is on the average, so far as humid climates are concerned, in contact with carbonated waters high in calcium and low in magnesium whose salts are derived from the decomposition of the rocks through which they circulate. In the light of experimental evidence, on the replacement of calcium carbonate by magnesium carbonate, where are the conditions more favorable for dolomitization by replacement, in the ocean or in the sea of underground water? Of course there are analyses of underground waters which show a high content of magnesium, which could possibly cause dolomitization, but these seem to be either exceptional or local.

C. EVOLUTION VERSUS THE METAMORPHISM OF LIMESTONES AFTER THEIR EMERGENCE FROM THE SEA AS EXPLANATION FOR THE INCREASE IN THE RATIO OF CALCIUM TO MAGNESIUM OF LIMESTONES AND DOLOMITES WITH GEOLOGIC TIME

Evidence has been presented for both the development of dolomite in the sea and its origin by the metamorphism of limestones after their emergence from the sea. Magnesian limestones can develop in the sea from a combination of organic and inorganic processes. The known inorganic processes are direct chemical precipitation, leaching, and secondary replacement. These may also be effected through the agency of underground water. Evidence has been presented to show that these processes are operative in the sea on a much larger and more uniform scale because of the chemical properties of the sea as compared with those of underground water. Underground waters derive their dissolved materials from the rocks through which they circulate, and generally

[1] From *Bull. 330, U.S. Geol. Survey*, 150.

are high in calcium and low in magnesium, whereas the sea derives its materials largely from the lands and not from the ocean bottom. Sea water is low in calcium and high in magnesium, and is therefore a more favorable as well as a more universal medium for effecting the dolomitization of the ocean bottom than is underground water for the dolomitization of the rocks through which it circulates. The direct evidence for the dolomitization of limestones by underground waters which has been presented shows only local dolomitization along fissures and other openings, principally in the belt of weathering or in localities permeated by waters of unique chemical compositions, such as hot magnesian springs. The occurrence of dolomites of vast thickness and extent and the interstratification of limestones and dolomites cannot therefore find a ready explanation in the mutative agency of underground waters. Excepting for certain local occurrences, dolomite formations seem to have developed in the sea, rather than by the metamorphism of limestones after their emergence from the sea. The evolution of dolomite and limestones through a decline in the deposition of dolomite with time, therefore, seems to have a high degree of probability. Consequently, the gradual alternation from the predominance of dolomite in the ancient sediments to the dominance of limestones of a high ratio of calcium to magnesium in more recent times has probably been due to gradual changes in the condition of deposition in the sea.

WHAT FACTORS CONTROLLING THE DEPOSITION OF CALCAREOUS MARINE DEPOSITS HAVE UNDERGONE A GRADUAL EVOLUTION RESULTING IN THE EVOLUTION OF THE LIMESTONES AND DOLOMITES?

Four factors directly control the composition of the materials precipitated on the ocean floor: namely, pressure, temperature, life processes, and the chemical composition of the sea. Which of these factors has undergone a progressive change, reflected in the evolution of limestone and dolomites? It is almost needless to consider whether the pressures on the ocean floor have undergone a progressive evolutionary change within geologic time. All the water-deposited sediments found on the continents appear to have

the character of deposits now forming in shallow or moderate depths. None are like the abysmal deposits of the present ocean, a forceful argument for the permanence of the continents and the oceans. Nor is there any probability that the temperature of the ocean has undergone a progressive change which would account for the evolution of limestones and dolomites. The continuity of the life record down to the base of the Cambrian precludes the possibility of any marked change in the temperature of the ocean throughout Zoic times. But even beyond the Cambrian this relative uniformity of temperature may have persisted for a period of time, as long or even longer than from the Cambrian to the present, for paleontologists believe that approximately nine-tenths of the evolution of life into main stocks was completed at the beginning of the Cambrian. All the phyla are represented in the Cambrian excepting the vertebrates, and the fact that no vertebrate fossils have been found in the Cambrian cannot be regarded as positive proof that even they did not exist at this remote period of earth history. On the other hand, more and more evidence is accumulating in favor of Chamberlin's philosophic conception that the temperature of the ocean and the climatic conditions of the continents have undergone oscillations in consequence of periodic, areal changes of the lands with respect to the sea; that periods of land expansion are characterized by zonal, diversified climates, tending toward world-wide aridity and refrigeration, while periods of maximum oceanic expansion are associated with climatic uniformity, moderation, and humidity. There is then no probability that the temperatures of the ocean have undergone an evolution consonant with the evolution of dolomite and limestone.

Could the evolution of living organisms have been the controlling factor in the evolution of limestones and dolomites?

It would be difficult to disprove that organic control was a factor in the problem. Organisms play a gigantic rôle in the distribution of lime at the present time, and have for ages past. Biologists, however, lend considerable support to the hypothesis that organic activities are adaptations to physical and chemical environment, rather than creators of environment. In the long run, they may cause profound changes in environment, but the

keynote of their activity is adaptation rather than control. The selection of potassa rather than soda by the land plants and the selection of soda in preference to potassa by marine plants has been cited as evidence for the adaptation of life processes to chemical environment. The preference of lime-secreting organisms for calcium rather than for magnesium may be a similar adaptation. It is suggestive that calcium carbonate is the principal salt contributed to the sea, and that in localities most favorable to life, lime carbonate is the most insoluble of the important salts of the sea. Recent biological studies have also shown that magnesium salts are to a certain extent deleterious to life processes. While the relation of life processes to environment is problematical, the evidence favors the physical control of life processes, rather than the control of environment by life processes.

Even if the immediate control of the evolution of carbonate rocks was largely by organic agencies, the causation of the control may logically be looked for in the environment. The change in the calcium magnesium ratio, which characterizes the evolution of the carbonate rocks, suggests under this hypothesis that it is related to a similar change in the calcium magnesium ratio of the materials contributed to the sea. It has been indicated already that waters containing a high proportion of magnesium to calcium are more efficient in causing the development of dolomite than those which do not. The salts of the sea are inherited from the metamorphic processes which have worked the earth over and over again. The circulation of the rock materials from one environment to another involves adaptations. The materials adapted to the new conditions tend to be stable. Others undergo conversion to new mineral forms. Some, finding no place in the new environment, are expelled and may finally reach the sea, where they again undergo environmental adaptations. Could it be possible that the ratio of river-borne calcium to magnesium, which is now approximately 6 to 1, has undergone an evolution throughout geologic times marked by a gradual increase in calcium and decrease in magnesium? A progressive change in the proportions of calcium and magnesium contributed to the sea might have been consummated either by a progressive change in the agents and processes of

metamorphism and sedimentation or by a progressive change in the calcium and magnesium content of the lands. It cannot very well be assumed that the nature of the agents and processes which contribute calcium and magnesium to the sea has undergone any marked change during geologic time. The continuity of the life record, the uniformity of sedimentation, and the duplication of climatic conditions down to the remote past speak against it. How then could the constitution of the lands, apparently the only remaining alternative, undergo a progressive change which in turn caused a progressive increase in the ratio of calcium and magnesium contributed to the sea, under uniformitarian processes? The answer to this problem is sought in the nature of the redistribution of calcium and magnesium in consequence of metamorphic and depositional processes.

[*To be continued*]

THE RECURRENCE OF TROPIDOLEPTUS CARINATUS IN THE CHEMUNG FAUNA OF VIRGINIA[1]

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For many years after the standard sections of the New York Devonian formations and their faunas had become well known, the brachiopod *Tropidoleptus carinatus* was supposed to be confined in its geologic range to the 1,100 or 1,200 feet of shale comprising the Hamilton formation in central New York. No trace of this fossil has ever been found in the typical Genesee and Portage faunas which follow the Hamilton fauna in west central New York. The entire absence of the species from the Genesee and western Portage faunas of New York seemed to indicate that the life of the species came to an end with the close of Hamilton sedimentation in central New York. But the discovery of *T. carinatus* in the Chemung of southern New York 2,000 feet above the top of the Hamilton by Professor H. S. Williams[2] several years ago proved that this species instead of becoming extinct at the close of the Hamilton had only changed its habitat. More recently Williams and Kindle[3] have found that *Tropidoleptus carinatus* and other well-known Hamilton species comprise the major part of the fauna at certain Chemung horizons in southern New York 2,000 feet or more above the top of the Hamilton formation. In this paper it will be shown that this and other Hamilton species reappear in the Chemung fauna of Virginia as they do in New York. The appearance of *T. carinatus* in the Chemung fauna of Virginia in abundance is especially notable because it is seldom found at the horizon of the Hamilton fauna so far to the southwest in this part of the Allegheny region as the occurrence in the rocks of Chemung time which will be described.

[1] Published by permission of the Director of the U.S. Geological Survey.

[2] *Bull. U.S. Geol. Survey No. 3* (1884), 24.

[3] *Amer. Jour. Science*, XIII (1902), 427–30; *Bull. U.S. Geol. Survey No. 210* (1903), 90–91.

This recurrent Hamilton fauna was collected in Bath County, Virginia, near Mountain Grove post-office. The relationship which it bears to the other faunas which are known in the section from which it comes will be indicated by the following section of the rocks exposed along Little Creek at Mountain Grove post-office.

SECTION AT MOUNTAIN GROVE, VA.

	Feet
h. Thin-bedded, hard, gray sandstone and interbedded shale	700
g. Thin-bedded, hard, gray sandstone and interbedded shale	100
f. Rather hard, sandy, dark-blue shale and some thin bands of sandstone with Portage fauna	600±
e. Black, hard fissile shale	100
d. Covered	70
c. Hard, black, and dark greenish-gray calcareous shale	6
b. Black, blocky, tough shale	20
a. Dark, coarse, ferruginous sandstone with frequent concretions of pyrites (Oriskany)	20+

The sandstone at the base of the section holds the usual type of Oriskany fossils and clearly represents the Oriskany sandstone. The fauna of the lower 26 feet of calcareous and blocky shale is rather meager in this section as compared with the rich fauna often found at this horizon. The species collected from it are the following:

FAUNULE *c*, MOUNTAIN GROVE, VA.

Orbiculoidea lodiensis media	*a*
Anoplotheca acutiplicata	*c*
Conularia sp.	*r*

This faunule taken alone, of course, could hardly be cited as satisfactory evidence of a definite horizon. An extended study[1] of the fauna found at this horizon by the writer throughout an extensive region in the Allegheny Mountains has shown, however, that the horizon is that of the Onondaga limestone. The greater part of the Hamilton horizon is covered in the section.

The next higher fauna which was collected from this section is shown in the following list of species from the lowest beds in the sandy shales marked *f* in the section outcropping at Cash's store.

[1] *The Onondaga Fauna of the Allegheny Region*, Bull. U.S. Geol. Survey (in press).

FAUNULE *f*, MOUNTAIN GROVE, VA.

Ontaria suborbicularis
Paracardium doris
Styliolina fissurella
Bactrites aciculum
Orthoceras sp.
Probloceras cf. lutheri
Tornoceras uniangulare

The student familiar with the western Portage or *Buchiola retrostriata*[1] fauna will at once recognize in this faunule a representative of that fauna. Its occurrence at a definite horizon in Virginia and Pennsylvania has been previously noted by the author.[2] Clarke[3] and Swartz[4] have recognized the same fauna in western Maryland. It should be noted here that the *Buchiola retrostriata* (*G. speciosa*) fauna listed by the author from the White Sulphur Springs, Virginia,[5] section is not the faunal equivalent of the *B. retrostriata* (*G. speciosa*) fauna of Williams,[6] but comprises only the upper portion of Williams' fauna. As the term is used by Professor Williams in Bulletin 244 it includes at least three distinct faunas, each of which has a fairly definite position in the sections. The writer's past and present usage makes it include only the latest of these three—the Portage—thus making it synonymous with the western Portage or Naples fauna of New York. The recorded range of this species makes it permissible to use the name in Professor Williams' comprehensive manner if it is desirable to consider these several faunas collectively. But the writer prefers the more restricted usage adopted by Professor Williams in an earlier paper,[7] according to which it includes only the western phase of the Portage fauna. The Portage fauna appears to characterize about 600 feet of the Mountain Grove section. Although the section is mostly exposed and the order of succession of the different parts is clear, the local buckling of

[1] This fauna has also been called the *Manticoceras intumescence* fauna and Naples fauna in New York.

[2] *Bull. U.S. Geol. Survey No. 244* (1905), 35, 40–41; *Jour. Geology*, XIV (1906), 633.

[3] *N.Y. State Mus. Mem. 6* (1904), 212.

[4] *Jour. Geology*, XVI (1908), 340.

[5] *Bull. U.S. Geol. Survey No. 244* (1905), 35.

[6] *Ibid.*, 51.

[7] *Bull. U.S. Geol. Survey No. 210* (1903), 115.

some of the softer beds leaves some uncertainty regarding the exact thickness of the section.

It is with the next fauna in the section that this paper is chiefly concerned. This fauna appears after the bluish-gray sandy shales and very thin sandstones have given place to very hard thin-bedded sandstones as the dominant lithologic characteristic of the section. In beds of this kind in division *g* of the section occurs the first appearance of the Chemung fauna. The following is a list of the species collected from this horizon:

FAUNULE *g*, MOUNTAIN GROVE, VA.

Productella sp.	*c*
Camarotoechia cf. congregata	*c*
Leiorhynchus sp.	*c*
Atrypa spinosa	*c*
Rhipidomella impressa	*r*
Rhipidomella cf. penelope	*r*
Schizophoria tioga	*c*
Ambocoelia umbonata	*c*
Schuchertella chemungensis	*r*
Delthyris mesacostalis	*c*
Spirifer medialis	*c*
Reticularia fimbriata	*r*
Tropidoleptus carinatus	*a*
Mytilarca chemungensis	*r*
Modiomorpha sp	*r*
Nuculites cf. oblongatus	*r*
Cyclonema sp.	

The stratigraphic position of this fauna several hundred feet above a typical Portage fauna shows plainly that it lies far above the Hamilton horizon. Its association with *Schizophoria tioga* and *Mytilarca chemungensis* indicates that it is here associated with a Chemung fauna. In the next division of the section above this we find *Spirifer disjunctus* and other well-known Chemung fossils as shown in the following list from division *h* of the section:

FAUNULE *h*, MOUNTAIN GROVE, VA.

Aulopora sp.	*r*
Chonetes scitula	*c*
Productella hirsuta	*c*

Atrypa spinosa	*c*
Stropheodonta (Douvillana) mucronatus	*a*
Stropheodonta perplana var. nervosa	*r*
Schizophoria tioga	*c*
Rhipidomella sp.	*r*
Camarotoechia sp.	*r*
Spirifer disjunctus	*c*
Edmondia sp.	*r*
Schizodus rhombeus	*r*
Sphenotus contractus	*c*
Loxonema sp.	*r*

The case of recurrence which has been cited involves a somewhat different phase of the phenomenon from that represented in the New York occurrences of *T. carinatus* in the Chemung.

The presence of a recurrent Hamilton species like *Tropidoleptus carinatus* in the Chemung fauna of southern New York involves its withdrawal from at least the major part of the New York area at the end of Hamilton sedimentation to some part of the sea furnishing a more congenial environment than that which accompanied Genesee and Portage sedimentation. In the newly adopted habitat or in a small portion of the old one it found a haven where those conditions of the Hamilton sea which were essential to its life were maintained throughout Genesee and Portage time. With the initiation of Chemung sedimentation *T. carinatus* extended its habitat back again over a part of the area which it had previously occupied.

The case of recurrence which I have given in Virginia does not involve, as in New York, a retreat of the species before unfavorable conditions at the close of the Hamilton and later recovery of lost territory, since it apparently never occupied this territory in Hamilton time. It represents instead the acquisition of a new habitat which had been outside the limits of its geographical range in the Hamilton sea. The writer's study of the Devonian faunas in the Allegheny region indicates that the typical Hamilton fauna with *T. carinatus* does not extend as far to the southwest as Mountain Grove, although the Hamilton sea extended much beyond that point to the southwest. The occurrence of a Hamilton species in abundance in the Chemung fauna of this part of Virginia thus

seems to indicate that the marine biotic conditions of the New York Hamilton and the Virginia Chemung seas were more nearly alike than they were in different parts of the same sea in the two states during Hamilton sedimentation.

A matter of some interest and importance in connection with the recurrence of this species and its associates relates to the location of its Portage habitat, or place of retreat between the close of Hamilton and the beginning of Chemung sedimentation. It has been shown by Prosser[1] and others[2] that in eastern New York the Hamilton fauna including *Tropidoleptus carinatus* continued in a slightly modified form to live on during Portage time. In other words, this species and some of its allies at the close of Hamilton time became extinct in central and western New York but survived in a narrow belt along the eastern margin of their old habitat and continued to live near the eastern shore of the Appalachian Gulf throughout Genesee and Portage time. (See Fig. 1.)

In Pennsylvania the writer's work has shown that the Ithaca and Portage faunas bear the same geographic and stratigraphic relations to each other that they do in New York. In western Pennsylvania the Portage formation is characterized by a typical western Portage or Naples fauna.[3] On the Susquehanna River an Ithaca fauna occupies the same horizon which is held by the Portage fauna in the Altoona section.[4] East of the Susquehanna River 35 miles, at Pine Grove, the writer has recently collected a faunule of the Ithaca fauna which shows a more prominent Hamilton element than the fauna exhibits at the Susquehanna River. It includes *Tropidoleptus carinatus*, as will be seen from the following list of its species:

[1] "The Classification and Distribution of the Hamilton and Chemung Series of Central and Eastern New York," *Fifteenth Ann. Rep. State Geol. New York* (1897), 208–14.

[2] H. S. Williams, "The Correlation of Geological Faunas," *Bull. U.S. Geol. Survey No. 210* (1903), 71–72; John M. Clarke, "The Ithaca Fauna of Central New York," *Bull. N.Y. State Mus. No. 82* (1905), 53–65.

[3] E. M. Kindle, "Faunas of the Devonian Section near Altoona, Pennsylvania," *Jour. Geology*, XIV (1906), 633.

[4] H. S. Williams and E. M. Kindle, "Contributions to Devonian Paleontology, 1903," *Bull. U.S. Geol. Survey No. 244* (1905), 69–92.

ITHACA FAUNA AT PINE GROVE, PENNSYLVANIA

Aulopora sp.	*r*
Cystodictya meeki	*c*
Chonetes scitula	*a*
Spirifer pennatus var. posterus	*a*
Tropidoleptus carinatus	*c*
Palaeoneilo plana	*c*
Modiomorpha cf. subalata	*r*
Goniophora minor	*r*
Paracyclas liratus	*r*
Actinopteria peristralis	*c*
Coleolus aciculum	*r*
Pleurotomaria capillaria	*r*
Pleurotomaria sulcomarginata	*c*
Murchisonia cf. leda	*r*

From central and eastern Pennsylvania the Ithaca fauna extends southward across Maryland far into Virginia. The Portage and Ithaca faunas occupy the same relative stratigraphic and geographic positions in this southerly area[1] as in New York state, the former having its maximum development to the westward of and parallel with the Ithaca fauna. Evidence that *Tropidoleptus carinatus* lived during Portage time near the eastern margin of the Appalachian Sea in Virginia as well as in Pennsylvania and New York is furnished by a collection representing the Ithaca fauna which the writer made at Bells Valley, Virginia. In this collection *T. carinatus* is a very abundant species, while another pre-Portage species, *Rhipidomella vanuxemi*, occurs sparingly with it.

The relation which *Tropidoleptus carinatus* bears to Hamilton, Portage, and Chemung sediments may be illustrated by the accompanying diagram which shows the easterly restriction of the species in New York during Portage time and the westerly extension of its habitat during Chemung time. The easterly or coastwise restriction of the species at the close of the Hamilton could be graphically shown for Pennsylvania and Maryland by diagrams of similar character, except that the Tully limestone would be omitted.

[1] E. M. Kindle, *Bull. U.S. Geol. Survey No. 244* (1905), 35, 41, faunules 1380*B* and 1382*D*; Charles K. Swartz, *Jour. Geology*, XVI (1908), 328–46.

When it is recalled that the geographic range of this species in the eastern United States during the Hamilton extended from the Hudson River and the eastern part of the Allegheny Mountains to Michigan, Indiana, and southwestern Illinois, it will be seen that its east-west distribution was reduced during Portage time to a very small fraction of that which it enjoyed during Hamilton time. Our present knowledge of its occurrence in the Chemung indicates that only a very small part of its east-west Hamilton range was regained during the Chemung. The north-south distribution of the species in the Allegheny region did not, however,

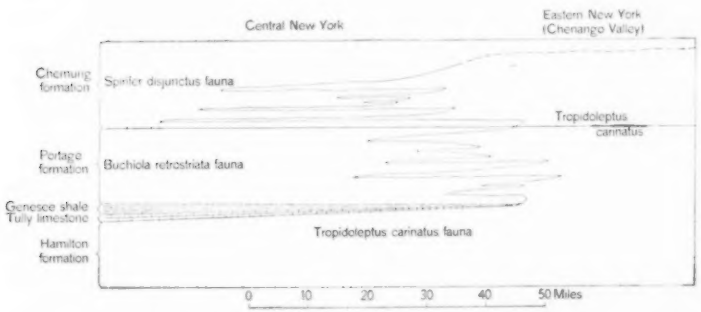


FIG. 1.—A diagrammatic east-west cross-section of the Middle and Upper Devonian of southern New York showing the relations of *Tropidoleptus carinatus* to the western faunas during Portage and Chemung time. Total thickness of the section is about 2,700 feet.

differ greatly during the Portage and Chemung epochs from what it had been during the Hamilton. In this direction it appears to have extended its range slightly in Chemung time beyond what it had been during Hamilton time. During Portage time the species was confined to a sublittoral belt, narrow but long, which reached south into Virginia along the eastern shore of the Appalachian sea. From the limits of this coastwise belt of the sea the more favorable conditions of environment which accompanied the initiation of Chemung sedimentation encouraged the migration of its colonies westward into the areas where we now find them in the Chemung of New York and Virginia. These colonies

appear to have experienced a succession of alternate extensions and withdrawals in the New York Chemung.

It is essential to a clear understanding of the interrelationship of these distinct but contemporaneous faunas to recognize the fact that zoölogical provinces were often as distinct in the Paleozoic seas as in those of the present. In the Devonian we know that there were such provinces, but as yet we know but little of their limits in any given epoch. We also know comparatively little about the factors which set the limits to faunal provinces. It is safe to conclude, however, that the recurrence of a fauna has been due to the oscillation or migration of the factors which conditioned its geographical distribution. Attention has been called to one of these factors by Ulrich[1] in discussing the recurrence of a Spergen fauna in the Ste. Genevieve limestone. He conceives one of the conditions inducing the recurrence of this fauna to have been "the subsidence or modification of barriers allowing communication with seas more permanently inhabitated by the invading fauna." The probable combination of two factors which are no doubt often effective in controlling recurrence is cited by Bagg in discussing the recurrence of a Cretaceous brachiopod in the Eocene of Maryland. Bagg[2] believes this case of recurrence to have been due to a deepening of the sea south of New Jersey, assisted perhaps by cold currents from the north which killed off the other Cretaceous species and encouraged the southward migration of a shell which previously had lived in the New Jersey region.

While the development or removal of land barriers and changes in the character of sediment have doubtless been at times influential in causing the recurrence of faunas, it is probable that changes in the temperature of marine waters have much more frequently been the direct effective agency in causing recurrence. Among the agencies controlling faunal distribution it is most probable that temperature has in the past, as in the present, been a factor of paramount importance. The recurrence of a species necessarily represents the recurrence of those factors in its environment which

[1] *Prof. Paper U.S. Geol. Survey No. 36* (1905), 49.

[2] *Am. Geologist*, XXII (1898), 272–373.

have throughout its life history controlled its distribution. Recurrent faunas, therefore, afford special opportunities to discover the factor most essential to the life of the fauna in a given case through elimination of those factors which are common to the sediments from which it is absent and in which it makes its earlier and later appearances. With reference to the sediments, the recurrence of a species after long absence from the section thus affords evidence of similar conditions having been present in widely separated formations, the importance and significance of which might otherwise not have been apparent.

In the light of these general considerations we may inquire into the cause of the eastward retreat of the species which has been shown to have occurred at the beginning of Genesee sedimentation and its later westward and southwestward migration. The evidence of such a movement has been cited on a preceding page. The close of Hamilton sedimentation is marked in western New York by a great change in the character of the sediments. The sandy and often calcareous shales of the Hamilton are succeeded by the thin band of the Tally limestone and the fissile black carbonaceous shales of the Genesee in the central and western parts of the state (see Fig. 1). When these black Genesee and the succeeding lighter-colored shales of the Portage are not entirely barren they are occupied by a fauna of "evident deep-water habit having nothing in common with the preceding Hamilton fauna."[1] These black shale sediments following the Hamilton extend southward beyond the Potomac River. This sharp contrast between the sediments and faunas of the Hamilton and those of the Genesee shales includes the total disappearance of the large coral fauna of the Hamilton. The annihilation at the close of the Hamilton of all fossils which, like corals, require shallow waters, and the shifting of those species which survived to the comparatively shallow coastwise waters points plainly to the deepening of the sea at the close of Hamilton time. Much additional evidence for the deep-sea conditions which prevailed during Genesee and Portage time in western New York

[1] John M. Clarke, "The Naples Fauna in Western New York," *N.Y. State Mus. Mem. No. 6* (1904), 211.

has been given by Dr. John M. Clarke[1] and requires no restatement here. A lower temperature of the water doubtless accompanied the deepening of the sea during early Genesee time and was probably the chief immediate cause of the complete disappearance of the shallow water fauna of the Hamilton from a large part of the Devonian sea with the appearance of the pelagic Genesee fauna. The sea became shallow again during Chemung time. This is shown by the ripple-marked sandstones which may be seen in Chemung sediments from New York to southern Virginia. That the remnant of the Hamilton fauna which had survived till Chemung time in the shallow coastwise waters in the eastern margin of the Devonian sea found in the Chemung sea a temperature similar to that of the old Hamilton sea is attested by such colonies as the one which has been described from Virginia.

The distribution of *Tropidoleptus carinatus* in the Chemung sediments as detached, often widely separated, colonies is in some degree comparable with that of *Ostrea virginica* along the present Atlantic coast. This warm-water species is unknown along wide stretches of the northern New England coast but in the Gulf of St. Lawrence flourishes in waters, which in their deeper parts afford a habitat for such Arctic forms as *Mya truncata*. That a low temperature is as essential to the life of the latter as is a high temperature to the former is illustrated by the fact that while in the Gulf of St. Lawrence *M. truncata* is found in the deeper waters only, in Greenland waters it is said to be sufficiently common at low water to furnish food for the Arctic fox and other land animals.[2] The character of the geographical conditions which permit representatives of the south Atlantic and north Atlantic coast faunas to live on adjacent parts of the sea bottom is indicated in the following quotation from Doctor MacBride.

> The whole north coast of Prince Edward Island is fringed by a series of parallel sand-bars, and it is owing to this circumstance that the oyster is able to flourish there. All who know the coast of the Gulf of St. Lawrence are aware that the water even in summer is very cold; so cold indeed that though

[1] *Op. cit.*

[2] J. F. Whiteaves, *Catalogue of the Marine Invertebra of Eastern Canada* (Geol. Surv. of Canada, 1901), 148.

the adult oyster could live in it, it could not reproduce itself, for the larvae would perish. But as the Gulf water flows over the sand-bars and shoals alluded to, it becomes heated up by the summer sun, and reaches a temperature which permits, in favorable years at least, of successful spawning. Oysters are accordingly confined to such places on the coast of Canada as present conditions similar to those mentioned above. They exist in the Baie de Chaleur, in some of the shallower inlets on the New Brunswick coast, at a few points on both shores of Prince Edward Island, and on the Northern Coast of Nova Scotia. In every case, however, we have to do with isolated colonies inhabiting warm spots surrounded by a great belt of cold water, so that although the larvae could be carried to great distances in the fortnight of their free-swimming life, they are all killed off by the cold.[1]

Protecting bars may at times have been a factor in modifying the temperature of the Devonian sea where Portage and Chemung colonies of *T. carinatus* gained a foothold, as they are now in sheltering the oyster at Prince Edward Island. But there can be no doubt that all times during the upper Devonian the eastern or coastwise belt of the Appalachian gulf was shallower than its more pelagic portion. Its waters must also have been comparatively warm, at least during the spawning season of its molluscan fauna. Since *Tropidoleptus carinatus* is confined in the late Devonian to the sediments of this belt of comparatively shallow sea, and consequently warmer water, we must conclude that its restriction and late survival here was due primarily to the higher average temperature of this part of the Devonian sea.

[1] E. W. MacBride, "The Canadian Oyster," *Canadian Rec. of Sci.*, IX (1903), 154–55.

FURTHER DATA ON THE STRATIGRAPHIC POSITION OF THE LANCE FORMATION ("CERATOPS BEDS")[1]

F. H. KNOWLTON

In June, 1909, I published a paper entitled: "The Stratigraphic Relations and Paleontology of the 'Hell Creek Beds,' 'Ceratops Beds,' and Equivalents, and Their Reference to the Fort Union Formation."[2] In that paper, as suggested by the title, the conclusion was reached that the beds considered—namely, the "Hell Creek beds," "Ceratops beds," "somber beds," and "Laramie" of many writers—are "stratigraphically, structurally, and paleontologically inseparable from the Fort Union, and are Eocene in age."

It was expected that this somewhat radical innovation would be received with a storm of protest, especially by the vertebrate paleontologists, but so far as known to the author only three papers have since appeared which deal specifically with the position of the "Ceratops beds." These comprise two papers by Dr. T. W. Stanton and one by Dr. O. P. Hay.

As two field seasons have intervened since the publication of my paper, during which important data were secured confirming the position there assigned the Lance formation,[3] it seems opportune to present the case as it now stands. The areas in which these observations were made are in the main in Eastern Wyoming and Eastern Montana and adjacent portions of North and South Dakota.

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] *Proc. Wash. Acad. Sci.*, XI (1909), 179–238.

[3] The name *Lance formation* has been formally adopted by the U.S. Geological Survey in place of the term "Lance Creek beds" or "Ceratops beds." Wherever *Lance formation* is employed in the following paper it is to be understood as including "Lance Creek beds," "Ceratops beds," "Hell Creek beds," "somber beds," "Lower Fort Union," and beds identified as "Laramie" by many writers.

NEAR THE MOUTH OF THE MEDICINE BOW RIVER, CARBON COUNTY, WYOMING

In the early nineties, when the late J. B. Hatcher was searching for new fields that might possibly supply additional material belonging to the then recently discovered group of horned dinosaurs (Ceratopsidae), he made an examination of the country lying along the North Platte River some twenty-five or thirty miles north of old Fort Fred Steele, in Carbon County, Wyoming. Hatcher observed fragmentary remains of dinosaurs at a point which he indicated[1] as "on the North Platte River opposite the mouth of the Medicine Bow River." As the dinosaurian remains were neither abundant nor well preserved, the country was not again visited until 1906, when a party from the United States Geological Survey, under the direction of Mr. A. C. Veatch, was engaged in investigating the coal resources of the so-called Carbon County coal-field. Veatch[2] published an outline geological map on which was shown the areal distribution of the formations involved. From this map it appeared that strictly speaking a point "opposite the mouth of the Medicine Bow River" would fall within Veatch's so-called "Lower Laramie,"[3] which is there 6,500 feet in thickness. Unfortunately Veatch did not collect any dinosaurian remains and thus settle definitely their position in this section, but from residents of the region who had known of Hatcher's discoveries it was pretty clearly indicated that they came from a series of low bluffs about a mile up the North Platte River from a point opposite the mouth of the Medicine Bow, in beds belonging to Veatch's so-called "Upper Laramie," which are in part at least the equivalent of the "Ceratops beds" of Converse County. The question of the absolute stratigraphic position of these dinosaur-bearing beds was thus held in abeyance until the past season (1910), when Dr. A. C. Peale and the writer spent ten days in the region, during which we secured data which settled

[1] *Am. Nat.*, XXX (1896), 118.

[2] *U.S. Geol. Surv., Bull. 316* (1907), 244, Pl. XIV.

[3] The "Lower Laramie" of Veatch is the same as the Laramie of the Denver Basin of Colorado as shown by its stratigraphic position and contained fossils. See Veatch, *Jour. Geol.*, XV (1907), 526–49.

the matter definitely. Incidentally it may be mentioned that we were able to confirm in every particular Veatch's mapping of the formations in this vicinity.

On the west side of the North Platte River, opposite the mouth of the Medicine Bow River, the bluff in the "Laramie" is about a mile back from the river. The beds, which consist of alternations of soft shales and beds of shaly brownish sandstones and numerous thin beds of coal, dip to the southeast at angles between 20° and 25°. From the bluff the surface slopes gently to the stream, and exhibits admirable exposures throughout. A very careful search was made of the "Lower Laramie" section, and although invertebrates pronounced by Dr. Stanton to be of "Laramie" age were found at numerous horizons, not a scrap of bone could be detected.

The contact between the "Lower Laramie" and "Upper Laramie" is very distinct and undoubtedly has been correctly placed by Veatch. There is a distinct change in the dip, apparently a slight change in the strike, and a marked change in the lithology between the lower and upper beds. The basal 300–400 feet of the beds above the line are composed of somber-colored soft sandstones and shales, often cross-bedded, with occasional small ironstone concretions, and in every way suggest the "Ceratops beds" to the northeast. Fragments of bone are scattered over the surface, and although no large pieces were secured at this particular point, enough was found to prove the presence of turtles, crocodiles, and dinosaurs. On the strike of these beds at a point about six miles southeast (T23N, R84W) we found in place about 300 feet above the base of the "Upper Laramie" beds a number of large vertebrae. These have been studied by Mr. C. W. Gilmore of the U.S. National Museum, and Mr. Barnum Brown of the American Museum of Natural History, and by both pronounced unqualifiedly to belong to *Triceratops*. It is not possible to fix with certainty the species to which these vertebrae belong, since the characters separating the species are drawn mainly from the skull, but Mr. Gilmore permits me to say that it is impossible to distinguish them from vertebrae of certain species from Converse County in which both skull and vertebrae are known. It

is quite possible that the skull of the individual of which we secured the vertebrae could be recovered by more extended excavation than we were able to make with the implements at hand.

Since, with the exception of their occurrence in the post-Laramie formations of the Denver Basin, the remains of *Triceratops* have never been found outside the Lance formation, the finding of *Triceratops* at this point is of far-reaching importance. It shows that not only are the beds containing them *above* more than 6,000 feet of "Laramie" rocks (the basal portion of which is almost certainly of Fox Hills age), but also that they are separated from the "Laramie" ("Lower Laramie") by an unconformity, which, according to Veatch,[1] is profound and has involved the removal of perhaps as much as 20,000 feet of sediments. This would seem effectively to dispose of the contention that the Lance formation ("Ceratops beds") is the equivalent of the Laramie.

The Lance formation—for such it must now be called—along the North Platte River above (south of) the mouth of the Medicine Bow, passes virtually without known stratigraphic break into beds which some twenty-five miles to the south have yielded Fort Union flora, thus showing the similarity of this section with all other known sections in which both Lance formation and Fort Union are present.

About 25 feet below the horizon of the *Triceratops* vertebrae, in the area under discussion, we collected the following species of plants:

Sabal grandifolia? Newb.
Populus amblyrhyncha Ward
Viburnum marginatum Lesq.
Sapindus sp.
Sassafras? sp. (Same as an unnamed species from the "Ceratops beds" of Converse County, Wyo.)

The palm, which is identified with some doubt as *Sabal grandifolia*, has a longer rachis than is usual in this species but is otherwise indistinguishable. It was described originally from the Fort Union near the mouth of the Yellowstone, and has been found subsequently at many localities in Montana, Wyoming, and Colo-

[1] *Am. Jour. Sci.*, XXIV (1907), 18.

rado. The *Populus* above mentioned has not been found outside the Fort Union. *Viburnum marginatum* was described first from Black Buttes, Wyoming, and has since been found in many places, among them several localities in the Lance formation of the Dakotas. The form identified as *Sassafras?* is a peculiar leaf and is apparently the same as an unnamed form from the Lance formation of Converse County. This analysis shows that three of the five forms noted in this collection are found in the Lance formation.

About five miles south of the above-mentioned *Triceratops* locality the "Upper Laramie" crosses the North Platte and the exposures are excellent. At this point the "Upper Laramie" consists of a great thickness of massive beds of yellowish and whitish sandstone, with much cross-bedding and abrupt changes from one color to another. Several hundred feet above the exposed base of this section we obtained a small collection of plants which embraces some three or four species, all of which are identical with undescribed forms from the Lance formation of Montana and the Dakotas.

The evidence of the plants is thus seen to confirm that of the vertebrates in correlating these beds with the Lance formation of Converse County and other areas in Montana and the Dakotas.

THE OLD STANDING ROCK AND CHEYENNE RIVER INDIAN RESERVATIONS

On the west side of the Missouri River, and lying between the Cannonball River on the north and the Cheyenne River on the south, is the area comprising in large part what was originally within the Standing Rock and Cheyenne River Indian Reservations. During the spring and early summer of 1909 this region was studied by a number of parties from the U.S. Geological Survey under the general charge of Mr. W. R. Calvert. The geology of this area is comparatively simple, the rocks being very little disturbed and at most comprising not more than four formations. Beginning with the lowest these are the Pierre shale, which is exposed in the valleys of most of the streams, and is overlain without stratigraphic break by the Fox Hills, which is the highest marine forma-

tion in the section. Above the Fox Hills, but, as will be shown later, with the intervention in places of a distinct unconformity, comes the Lance formation, above which, but without unconformity or other observed break, is the acknowledged Fort Union.

In the present connection the principal interest naturally centers in the Lance formation, and more particularly as regards its relation with the underlying Fox Hills. Mr. Calvert, who is not only familiar with the area in question but with adjacent areas in North Dakota and Montana where similar conditions obtain, has kindly prepared the following statement:

"Stratigraphic work by field parties in immediate charge of A. L. Beekly, Max A. Pishel, and V. H. Barnett in the Standing Rock and Cheyenne River Indian Reservations of North and South Dakota in 1909 and similar investigation in eastern Montana in 1910 in charge of Max A. Pishel and C. F. Bowen gave opportunity to study the relationship of several formations concerning which discussion has arisen periodically for a number of years, and which is of special interest in view of its direct connection with geologic history at the close of the Cretaceous. The region studied in the Dakotas includes the type locality of the Fox Hills sandstone and is adjacent to the type locality for the Pierre shale. Where the full section of the Fox Hills is present it usually comprises a gradation at the base from the somber shale of the typical Pierre into a more or less massive sandstone. This sandstone member is overlain by 25 feet or more of banded shale overlain in turn by a massive sandstone, constituting what in the field was considered the top member of the Fox Hills. Fossils occur only sparingly in the lower sandstone and in the banded shale, whereas the top sandstone is prolifically fossiliferous, the fossils being found most abundantly at or near the top of that member. Normally overlying this fossiliferous horizon is a sequence of beds entirely dissimilar in lithology from the underlying Fox Hills, and it is concerning these beds that question has arisen relative to their exact position in the geologic column. These strata constitute the Lance formation to which the name 'somber beds' has been applied in various previous publications.

"From the standpoint of lithologic character the term 'somber

beds' is very applicable, as the strata are made up chiefly of gray to dark clays and muds with intercalated lenticular sandstone members. There is rapid horizontal alteration in character of material so that a section measured at any one locality does not compare in detail with one measured a short distance away. Carbonaceous zones occur at frequent vertical intervals and the lowest few feet of the formation is almost invariably a lignitic zone.

"As a result of field study by Pishel, Barnett, and the writer, it seems certain that the line between the Fox Hills sandstone and the Lance formation is marked by an unconformity, but the import of that unconformity is of course a matter for the paleontologist rather than for the stratigrapher to decide. However, the evidence gathered by the stratigrapher may possibly have some weight in arriving at a conclusion, and that evidence is here presented.

"The maximum thickness of the Fox Hills sandstone is in the neighborhood of 200 feet, but it was found in the field that this measurement is entirely too great for certain localities. On Worthless Creek, in T16N, R20E, Black Hills Meridian, exposures are especially good and it was here that the most striking example of unconformity between the Fox Hills and Lance formation was observed. On the west side of Worthless Creek Valley, near the line between sections 25 and 26, it was noted that the 'somber beds' of the Lance formation transgressed across the Fox Hills sandstone and that the upper part of the latter formation down to the banded shale member was absent. The unconformity at this locality is angular as well as erosional, for the banded shale dips to the north at a 4-degree angle, whereas the 'somber beds' are horizontal. Within a horizontal distance of 500 feet the 'somber beds' fill a channel eroded in the banded shale of the Fox Hills, so that the total vertical amount of combined transgression and erosion is more than 40 feet. On the opposite side of the valley the total thickness of undoubted Fox Hills is even less, for it appears that the lignitic zone of the 'somber beds' rests on Pierre shale. In any event there is surely less than 25 feet of the Fox Hills present at this place. In view of the fact that the Fox Hills sandstone is normally at least 150 feet thick it would seem that

the erosion interval represented is of considerable magnitude, or else that the formation is peculiarly variable in thickness.

"In general the zone along the contact between the Fox Hills sandstone and the Lance formation is poorly exposed in this region, but in the majority of localities where exposures were adequate careful study disclosed evidence that deposition was not continuous from one formation into the other. In a paper[1] on this subject Doctor Stanton admits the occurrence of an unconformity at this horizon in the Dakotas but attaches no particular significance thereto, stating that channeling would normally be expected in the change from marine to land conditions and giving especial weight to the fact that a marine Fox Hills fauna is found commingled with brackish-water types above the unconformity. He states that 'The paleontologic evidence consists of distinctive Fox Hills species belonging to such marine genera as Scaphites, Lunatia, and Tancredia, found directly associated in the same bed with the brackish-water forms and occurring with them in such a way that they must have lived together or near each other and been imbedded at the same time.'

"From the above quotation the inference is plain that Dr. Stanton concludes that the faunal evidence demonstrates with a fair degree of certainty that the unconformity is of minor rather than of major significance. To this conclusion the stratigrapher, is, of course, not qualified to object with authority, but it seems to the writer that the evidence may be looked at from two divergent points of view. Because Fox Hills fossils occur in the lignitic shales at the base of the 'somber beds' and mingled with the brackish water types of the Lance formation is not necessarily proof positive that the various faunas lived at the same time; for if the deposition of the Fox Hills was followed by a definite erosion interval, what is more probable than that in the deposition of succeeding strata fossil shells would be eroded from the marine beds and carried into channels, there to mingle with the then living brackish-water fauna of the Lance formation?

[1] T. W. Stanton, "Fox Hills Sandstone and Lance Formation ('Ceratops Beds') in South Dakota, North Dakota and Eastern Wyoming," *Am. Jour. Sci.*, XXX (1910), 178.

"That the unconformity at this critical horizon is of more than local significance is borne out in large measure by observations made in the course of an examination of the lignite region in eastern Montana in 1910. Trending southeast from Yellowstone River, 10 miles southwest of Glendive, is an anticline which extends to the South Dakota line and along which the Lance formation is exposed in a zone on either side. Along the axis of this anticline Pierre shale is at the surface in a band several miles in width with a sandstone formation appearing as a zone of outcrop between it and the Lance. Although fossils have not been found in this sandstone it is believed to be the equivalent of the Fox Hills in

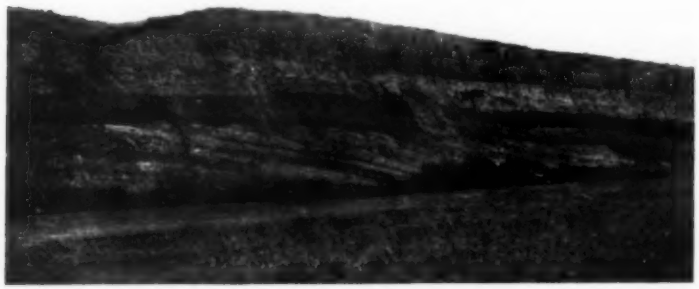


FIG. 1.—South bank Moreau River, near Govert P.O., South Dakota, showing angular unconformity between Lance and underlying beds identified as Fox Hills. Photograph by Barnett.

its type locality. Transition into it from the Pierre shale is perfect, and as in the Dakotas it is overlain by the markedly dissimilar strata composed of alternating lenticular sandstone, somber clays, and carbonaceous zones. In at least two localities in this region the upper surface of the sandstone referred to the Fox Hills is irregular and with every appearance that sedimentation between that formation and the overlying Lance formation was interrupted. These were noted and mapped by Pishel and Bowen and are in Sec. 22, T6N, R60E, Sec. 32, T7N, R61R. The amount of erosion is not great in either case, but in the opinion of the writer the occurrence of an unconformity in this region at appar-

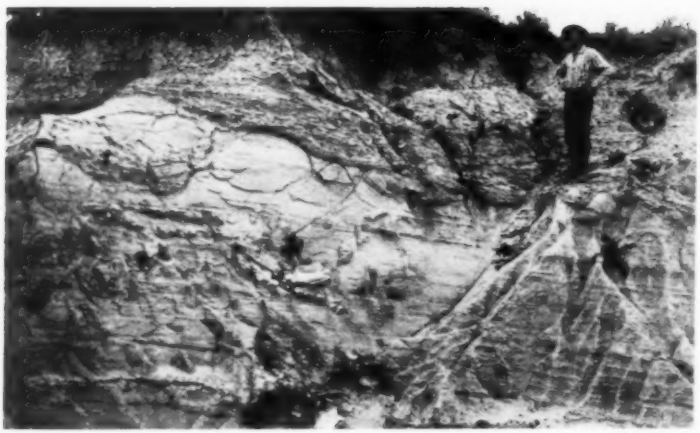
ently the same horizon as that in the Dakotas tends to show that the break has more than local significance."

The observations recorded by Mr. Calvert in the eastern portion of this South Dakota field were supplemented and extended to the western part of the state by Mr. V. H. Barnett in 1910, while making a hasty reconnaissance trip across the country. For instance, on the south bank of the Moreau River, near Govert P.O., in Sec. 21, T15N, R8E, South Dakota, Mr. Barnett found what is perhaps the most marked evidence yet recorded of unconformable relations between beds thought to be Fox Hills and the Lance formation. Mr. Barnett traced the Lance formation continuously from the central part of the state to the point mentioned above, where it was found practically horizontal, while the underlying beds dip to the northwest at an angle of about 10°. These underlying beds appear to be in the stratigraphic position of, and lithologically similar to, beds resting immediately on Pierre shale, at Hoover, about 10 miles southwest, and there is no reasonable doubt regarding their age, but no paleontologic evidence was secured—or sought—at this locality. If the beds are not of Fox Hills age they must be older, which would indicate an unconformity of even greater magnitude than is presumed. Mr. Barnett secured a photograph of this section which he has kindly permitted me to reproduce here as Fig. 1. The full section of the supposed Fox Hills is not exposed at this point, but some distance west, at Castle Rock Butte (T12N., R5E), the following section was measured; Pierre 50 feet; Fox Hills 125 feet; Lance formation 140 feet, the latter overlain by higher Tertiary.

The unconformity spoken of above by Calvert as occurring in Sec. 32, T7N, R61E, in Custer County, Montana, is on the west side of the anticline extending southeast from Glendive. It is clearly shown in the accompanying Figs. 2, 3, the negatives of which were made by Mr. C. F. Bowen, by whose consent they are included here. The Fox Hills with a thickness of about 70 feet dips at an angle of 5°, while the overlying Lance formation is horizontal.

Mr. Calvert's observations concerning the occurrence of the marine Fox Hills invertebrates in the basal members of the Lance

formation may be briefly alluded to. It appears that in the hundreds of localities throughout the Dakotas, Wyoming, and Montana at which the contact between Fox Hills and the Lance



FIGS. 2, 3.—Eastern part of Custer County, Montana, showing erosional unconformity between Fox Hills and Lance. Photographs by Bowen.

formation has been examined, only five localities, all within a limited area in South Dakota, have been noted in which the marine Fox Hills invertebrates occur above the acknowledged top of the Fox Hills, where they are often found commingled with certain

brackish-water forms. It does not appear that they have ever been found at a greater distance than 12 or 15 feet above the top of the Fox Hills, and since it further appears that in none of the four sections given[1] does the Fox Hills exceed 115 feet in thickness, there is every probability that they were re-deposited in the channeled upper surface of the Fox Hills and that they did not live in association with the brackish-water forms with which they are now found entombed.

The plant collections obtained from the Lance formation by Mr. Calvert and the members of the several parties under his charge show conclusively that the relation of this flora is unmistakably with the Fort Union. In fact with the information at hand regarding distribution it is practically impossible without stratigraphic data to distinguish between the flora of the Lance formation and that of the acknowledged Fort Union. The lists of these collections follow:

[5437]. NW ¼ Sec. 5, T2N, R88W, S. Dakota. North bank of Cannonball River, at McCord coal-bank, 150 feet above base of beds.

Sequoia nordenskiöldi Heer
Thuya interrupta Newb.
Glyptostrobus europaeus Unger
Populus speciosa Newb.
Populus amblyrhyncha Ward
Paliurus colombi? Heer
Sapindus grandifoliolus Ward
Celastrus alnifolia? Ward
Juglans sp.?
2 new forms, gen.?

[5443]. SW ¼ Sec. 23, T23N, R21E, Black Hills Meridian, 150 feet above base of beds.

Sequoia nordenskiöldi Heer
Leguminosites arachnioides Lesq.

[5444]. Near ¼ cor. E. side Sec. 13, T22N, R22E. Black Hills Meridian. 125 feet above base of beds.

2 or 3 of same species as unnamed forms from the "somber beds" at Glendive, Montana.

[5430]. Rattlesnake Butte, Cheyenne Indian Reservation, S. Dakota. 100 feet above base of beds.

Glyptostrobus europaeus Newb.
Taxodium occidentale Newb.

[1] *Am. Jour. Sci.*, XXX (1910), 174–77.

Viburnum marginatum Lesq.
Cornus newberryi Hollick
Salix sp.
Quercus sp.
3 or 4 forms that are identical with unnamed species from Glendive, Montana.

[5422]. Near SE ¼ Sec. 20, T14N, R19E, Black Hills Meridian, S. Dakota. 100 feet or less above base of beds.
Sequoia nordenskiöldi? Heer
Sequoia langsdorfii Heer
Platanus platanoides? (Lesq.) Kn.
Viburnum sp. (same as new species from Lance of Converse County, Wyoming).
Lauraceous leaf (same as form found in "somber beds" at Glendive, Montana).

[5431]. SW ¼ Sec. 4, T19N, R18E, S. Dakota. 300 feet above base of beds.
Thuya interrupta Newb.
Populus amblyrhyncha? Ward
Viburnum elongatum Ward
Viburnum sp.?
Grewiopsis whitei? Ward

[5432]. SE ¼ Sec. 25, T20N, R18E, S. Dakota. 300 feet above base of beds.
Sequoia nordenskiöldi? Heer
Zizyphus cf. Z. hyperboreus Heer
Populus? sp.
Platanus? sp.

[5433]. Sec. 33, T20N, R20E, S. Dakota. 150 feet above base of beds.
Ginkgo adiantoides Heer
Platanus raynoldsii? Newb.
Sapindus grandifoliolus? Ward
Viburnum (apparently same as unnamed species from Lance of Converse County, Wyoming).

[5434]. SE ¼ Sec. 12, T19N, R24E, S. Dakota. Base of beds.
3 fragmentary leaves, apparently same horizon as No. 5436.

[5436]. NE cor. Sec. 7, T17N, R24E, S. Dakota. Base of beds.
Platanus haydenii Newb.
Viburnum elongatum Ward
Viburnum marginatum? Lesq.
Sapindus grandifoliolus? Ward
Dombeyopsis sp.
Polygonum? sp.
Lauraceous leaf like that of Glendive, Montana
2 species same as unnamed form from Glendive

[5423]. South of Moreau River about 7 miles above Thunder Butte P.O., S. Dakota.

Sec. 35, T14N, R19E. Lower 4 feet of Lance formation.

Thuya interrupta Newb.
Sequoia nordenskiöldi Heer
Sequoia acuminata? Lesq.
Populus cuneata Newb.
Viburnum marginatum? Lesq.
Leguminosites? n. sp.
Cyperacites sp.
Monocotyledon—new

It needs but a glance at the above lists to show how preponderating is the Fort Union facies.

CONVERSE COUNTY, WYOMING

Although Converse County, Wyoming, is the type locality for the Lance formation, and has been visited again and again by geologists and paleontologists, it is still a perennial source of discussion and difference of opinion. From the first, difficulty has been experienced in drawing the line between the highest marine formation—the Fox Hills—and the overlying dinosaur-bearing beds. The Fox Hills was estimated by Hatcher to have a thickness of 500 feet, and consists of an alternating series of sandstones and shales, with massive sandstones at the top which contain numerous large concretions and a rich marine fauna of characteristic Fox Hills species. The upper line was drawn somewhat arbitrarily at a six-inch band of hard sandstone which was thought to separate the fossil-bearing Fox Hills sandstone below from similar but supposedly non-fossiliferous sandstones above. When Dr. Stanton and I visited this region in 1896 we failed to secure evidence for changing the top line of the Fox Hills as established by Hatcher, though we did find four species of brackish-water invertebrates in clays above a forty-foot bed of massive sandstone over 400 feet above the highest fossiliferous Fox Hills horizon in that particular section.

So the question rested until 1909, when Messrs. M. R. Campbell, T. W. Stanton, and R. W. Stone spent nearly a week in the region. Their principal contribution to the knowledge of the

stratigraphy of the area was, according to Stanton,[1] "the discovery that the marine Fox Hills deposits extend about 400 feet higher than had previously been determined, and that non-marine coal-forming conditions were temporarily inaugurated here before the close of Fox Hills time." If Hatcher's estimate of the thickness of the beds assigned by him to the Fox Hills was anywhere near correct this "discovery" would seem to increase the total thickness to about 900 feet, yet nowhere in the paper mentioned is a thickness greater than 400 or 500 feet claimed for it. This appears difficult to explain unless the lower as well as the upper limit of the formation has been changed.

A number of sections are given by Dr. Stanton, in one of which at least, namely that on Buck Creek, the top of the Fox Hills appears to have been fixed by the presence of the plant *Halymenites major*. The thickness of the Fox Hills in this section is given as 505 feet, though the highest horizon at which marine Fox Hills invertebrates occur is about 180 feet below the top.

In the section made on the divide between Lance and Buck Creeks the Fox Hills is said to have a thickness of 445 feet, though the lower member of the section only (30 feet above the Pierre shale) is indicated as containing a Fox Hills fauna.

The section made on the south side of the Cheyenne River at the mouth of Lance Creek shows a thickness of 405 feet of Fox Hills above the Pierre, but the highest point in the section at which marine Fox Hills invertebrates were found is over 100 feet below the top. It further appears from this section that the upper four members, aggregating 115 feet in thickness, contain carbonaceous and lignitic shales as well as fragments of dinosaur bone and brackish-water invertebrates, certain of which are the same as those found in, and there said to indicate the Laramie age of, the 400 feet of beds already mentioned as reported by Stanton and Knowlton above the typical marine Fox Hills.[2] To the writer it seems altogether more probable that the four upper members of this section belong to the Lance formation and not to the Fox Hills, and it appears that this was the view at first entertained by Dr.

[1] *Am. Jour. Sci.*, XXX (1910), 184.

[2] *Bull. Geol. Soc. Am.*, VIII (1897), 130.

Stanton, who says,[1] "When studying the section it was believed that the upper four members belong to the Lance formation, but afterward when comparison was made with sections of the south end of the field it seemed more possible that all the beds examined here belong to the Fox Hills." If this portion of the section is placed in the Lance formation, where it certainly appears to belong, the thickness of the Fox Hills in the section is reduced to 285 feet, or but little more than half of the maximum thickness assigned to beds of this age in the Converse County region. While this evidence may not be considered conclusive, it must at least be admitted that it strongly suggests the possibility that even here, as in the areas already discussed in the Dakotas and Montana, the Fox Hills is of variable thickness, due to the erosion of the upper portions before the deposition of the Lance formation.

It is to be admitted, however, that all who have studied the Converse County areas have had, and still have, difficulty in fixing the upper line of the Fox Hills, but in this connection it is to be pointed out that while many students have visited or collected in the region, it still awaits the careful, painstaking study that has been given other fields, such, for instance, as the areas in the Dakotas and Eastern Montana, which have been described by Mr. Calvert. And in this connection it may be mentioned that although in Converse County the exact location and extent of the unconformity between Fox Hills and Lance is not definitely known, the time interval is undoubtedly indicated, since 150 miles to the southeast (i.e., opposite the mouth of the Medicine Bow River) the same dinosaur-bearing beds are above an unconformity which separates them from 6,000 feet of unquestioned "Laramie," while 100 miles to the east in the Dakotas, the Lance formation rests on an uneven surface which in some cases represents the removal of practically the whole thickness of the Fox Hills of the region.

As a possible explanation of the difficulty experienced in detecting the presence of the unconformity between the Fox Hills and overlying Lance formation in this area, the following facts may be offered: the localities in Eastern Montana and Western South Dakota where the examples of the distinct angular and erosional

[1] *Am. Jour. Sci.*, XXX (1910), 185.

unconformity are so well exhibited are all adjacent to the anticlinal uplift which Calvert has shown extends southeast from the vicinity of Glendive, Montana, to the western line of the Dakotas. Here the uplift tilted the beds and accelerated the erosion, while in the flat country to the westward in Converse County and adjacent areas, the erosion of the Fox Hills was relatively uniform, and when the Lance formation was later laid down over this surface the unconformable relations are difficult of detection. But as Cross long ago stated:[1] "The visible conformity between the Ceratops beds and Fox Hills in Converse County cannot be accepted, contrary to other evidence, as proving the former to have been deposited in the epoch next succeeding the Fox Hills."

UPPER LIMIT OF THE LANCE FORMATION

In my original paper on the Lance formation ("Ceratops beds") I stated that everywhere throughout the vast region studied it was found conformably overlain by the acknowledged "yellow" Fort Union, adding that "of the many workers who have observed the field relations at hundreds of points, not one, so far as known to the writer, has recorded the presence of unconformity between them." Field work during the past two seasons has confirmed this statement in every particular, and there is yet to be observed a single locality at which unconformable relations have been even suspected. Hence it seems to have been demonstrated that sedimentation from one to the other was continuous and uninterrupted.

At the time the original paper was published it was thought that the Lance formation and the acknowledged Fort Union (the lower and upper members of the Fort Union as they were there called) might usually be separated on lithologic grounds, the lower being generally dark and somber-colored and the upper usually yellow. Subsequent investigation, however, has failed to confirm this, for while in individual sections, or even within limited areas, a provisional lithologic separation may often be made, when regional studies were undertaken it was found that the lithologic difference was so variable within short distances as to be wholly

[1] *U.S. Geol. Survey, Mon. 27* (1896), 236.

unreliable. For instance when a coal-bed that occurred near the top of the so-called somber-colored Lance formation was traced accurately for only a few miles it was found that the position of the dark-colored and the yellow beds varied as much as 300 feet, that is, at one point, the coal-bed might be 150 feet down in the somber-colored portion, and at another, an equal distance up in the yellow beds. It may therefore be confidently stated that the Lance formation and acknowledged Fort Union cannot be separated formationally on either structural or lithologic grounds, though in general the lower beds are on the whole prevailingly somber in color, while the upper beds are prevailingly yellow.

MAGNITUDE OF UNCONFORMITY AND BOUNDARY BETWEEN CRETACEOUS AND TERTIARY

Having demonstrated the existence of unconformable relations between the Lance formation and the underlying formations, the question naturally arises as to the magnitude of this discordance. By some it is claimed that it is merely local and is not more important than other breaks said to occur at various intervals in the Lance formation, and the doubt is expressed whether, even if the unconformity is present, any great amount of erosion is indicated.

The wide area over which its existence has now been demonstrated certainly removes it from the category of "local" happenings, and the uniformity of its occurrence beneath the Lance formation is sufficient indication of its importance over any that have been thus far even apparently indicated within the formation. Now as to its magnitude. It has been shown that in Carbon County, Wyoming, the Lance formation is not only above the full thickness of the "Laramie" (6,000 feet) but is separated from it by an unconformity that Veatch states is fully 20,000 feet, and moreover this unconformity is in the same position as regards the Laramie as that in the Denver Basin of Colorado, which, according to Cross, has involved the removal of from 12,000 to 15,000 feet of strata between the Laramie and overlying formations. It is possible that the figures given by Cross and Veatch may be too high, but even so, the unconformity is undoubtedly one of importance, and this would seem to dispose of the contention that

the Lance, Arapahoe and Denver formations may be mere "phases of the Laramie." Whether the Laramie and various post-Laramie beds were deposited and later removed throughout the Dakotas, Montana, and Wyoming, is not at present known, but certain it is that the unconformity at the base of the Lance formation represents the time interval during which in other areas they were laid down and subsequently removed in whole or in part. Therefore, in the opinion of the writer, this unconformity is an important one and must be so recognized in American geology.

Since it has been demonstrated that the Lance formation is so inseparably associated with the Fort Union—that is, without a trace of an unconformity—and is separated from the underlying formations by an unconformity of such extent, this point becomes more clearly than ever the logical point at which to draw the line between Cretaceous and Tertiary. In establishing this line the stratigraphic, lithologic, and paleobotanical criteria are believed to be more competent than any other evidence thus far brought forward.

LARGE GLACIAL BOWLDERS

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Mention of large glacial bowlders is not uncommon. In fact most localities glaciated have their "largest in the state." Some lie so as to reveal easily the fact that they have been transported. Others are more or less concealed, and some care is needed to determine whether the rock is really a transported mass or country rock in place.

A mass of limestone in Ohio covering about three-quarters of an acre, and in places sixteen feet or more in thickness, was mentioned by Orton in one of the older reports of Ohio geology and cited by Dana.[1] In the Alps was found a mass containing about 200,000 cubic feet of rock or enough to cover a fourth of an acre twenty feet deep.[2] Sardeson[3] reports a block of limestone moved a short distance whose width was over 100 feet, thickness several feet, and length unknown. Limestone bowlders, often large masses, are quite common in parts of Illinois, specifically in western Livingston County, in northern McLean, and in parts of Champaign, Ford, and Vermilion counties. Following is a detailed description of several masses or "pockets" of this rock which have been studied.

On the south side of the Champaign-Ford county line one and one-half miles east of the northwest corner of Ludlow township are the remains of a large "pocket." H. H. Atwood of Paxton who owns the farm says several loads of the rock have been drawn away for building purposes, but enough remains to mark the place distinctly.

Near Saybrook, McLean County, are a number of localities where limestone is found at the surface. On the farm of Mr. Riggs,

[1] J. D. Dana, *Manual of Geology*, 5th ed. (1895), 960.

[2] *Ibid.*, 248.

[3] *Jour. Geol.* (1905), XIII, 351–57.

one mile north and one and one-half miles west of Saybrook, lime was burned forty or fifty years ago. A small kiln was built and operated several years with rock from this deposit. A half-mile east of this kiln, past the schoolhouse, another "pocket" was opened and several loads drawn some thirty-five years ago. At present but few know of these limestone pits, for they have been entirely dug out and the holes are plowed over. Portions of the kilns and fragments of waste alone remain.

Two miles north and one mile west from Saybrook are a number of slabs resembling flagging. These are quite numerous on one farm. On a farm ten miles west of Saybrook lime was burned for the local market, but at present the rock is apparently exhausted. In this locality, a good many loads for foundations and well curbs have also been drawn away. According to a boring for Mr. H. Cheney of Saybrook, bed rock was struck here at a depth of 236 feet. It is recorded that a five-foot limestone bowlder was struck in a gravel bed at a depth of 150 feet. A well digger here in conversation said that in digging wells he frequently encountered limestone bowlders of various sizes, and noted several localities where the bowlder weighed from ten to twenty tons. A number of wells in the vicinity have been walled with the rock taken out in digging, supplemented with more found near by. "In fact," he says, "there is lots of limestone scattered all over the country." No bed rock, however, has ever been found about Saybrook except at considerable depths as in the well cited, 236 feet.[1] With such thickness of drift as this, these masses of limestone cannot be in place.

The largest drift mass of limestone is in Livingston County, about a mile and a half southwest of Fairbury, where Dr. Brewer has been taking out a great deal of limestone. The mass is along a small stream where the water divides, flowing around a little island. On the north bank of the south division and on both banks of the north division, rock is found; but on the extreme south bank no rock is known, nor is rock struck in any wells on the south side of the stream. Along the stream on the north side *for*

[1] Frank Leverett, *U.S.G.S. Mon. 38*, 695, reports a boring for coal here reaching rock at 247 feet.

a half-mile or more, and back from the stream a half-mile, all wells strike rock at some twelve to sixteen feet. Below the rock at the quarry is clay, a soft sticky yellow body, called by the quarrymen "soapstone." Examination showed it to be glacial drift. No large pieces of rock can be obtained in the quarry, for the whole mass is shattered. The pieces vary in size from ten or fifteen to two hundred and fifty pounds, rarely larger than can be handled by one man. At the quarry the rock is from ten to fifteen feet thick, and two or three nearby wells are reported passing through it, one finding sixteen feet of rock.

The rock seems to be almost exactly horizontal in the quarry, and it is struck at quite uniform depths in the neighboring wells. Inquiry for this stratum in the coal shafts, two in number, at Fairbury, failed to reveal its presence. One about a mile distant encountered a piece of rock at a depth of forty feet, but below it was more clay. The other about one and one-quarter miles distant found no rock for at least ninety feet.

At McDowell a little quarry is operated in rock which has almost precisely the same characters as the one at Fairbury, but it is of less extent—ten or twelve feet thick, shattered and local. West and south of McDowell about two miles from Ocoya there are two or three little quarries opened. One near a little stream is operated by two men who have taken out over a hundred cords of rock in a single summer. The rock is eighteen feet thick at a maximum, but in places only five or six feet thick. Some parts of it are shelly or shattered, but toward the bottom, this mass is firmer than any other yet considered. Sometimes pieces twelve to sixteen inches thick and six to eight feet long are removed, but no blasting is done. The near proximity to the stream caused some trouble with water seepage, so a sumpf was dug through the rock and a pump put in. A crowbar was thrust down easily in the bottom of this sumpf two or three feet. The quarrymen say the substratum is "soapstone of variable character," but it seems to be a well-packed, blue, pebbly clay with a greasy feel. That it is not one of the soft argillaceous layers of the Coal Measure rocks is shown by its pebbles. The edge of the rock is known in two directions. The edge along the stream is slanting, the other,

nearly at right angles thereto and on the east end of the quarry, is perpendicular and very regular. Rock is struck in but one well in the vicinity. Rock has been taken out from similar, though smaller local pockets, in two other localities within 80 rods.

The county surveyor of Livingston County says there are a good many local deposits along the Vermilion River, slabs, bowlders, and irregular pieces, but it is not continuous, and the layers are variously tilted.

Usually these large masses are along morainal ridges. Sometimes they are found along stream beds where they have been exposed by erosion. They cover areas varying from a few rods to over a hundred acres in extent, and differ in thickness from six or eight feet to eighteen or twenty feet. They are always in a shattered condition; often very much broken up, but sometines requiring some blasting to get out the rock. What seems the most surprising thing is that there is rarely much dip. The bedding in all the larger masses is almost horizontal. During early days when transportation was expensive, these masses of limestone were much used by the settlers, who made lime from some of them, and from others drew building material. The rock was more workable, and hence more desirable, than the granite bowlders.

Their presence in the drift, and their distribution mostly in the large recessional moraines, seems to point to a glacial origin for them. Since most if not all the masses mentioned are of Carboniferous rock, as shown by their fossils, the sources could not have been more than fifty to seventy-five miles north, for beyond that limit there is no Carboniferous rock, from which they could have come. While no specific places have been found from which it is thought these large bowlders were plucked, it is believed that they may have come readily from the bluffs of a valley, or from hills a moderate distance to the north.

Reviews

Iron Ores, Fuels and Fluxes of the Birmingham District, Alabama. By Ernest F. Burchard and Charles Butts. With Chapters on the "Origin of the Ores," by Edwin C. Eckel. Bull. U.S. Geol. Surv. No. 400. Pp. 204.

The Birmingham District, as here considered, extends as a long, narrow belt, about seventy-five miles in length by ten in width. The iron ores of the district lie in the broad, anticlinal Birmingham Valley which is structurally a part of the Appalachian Valley. An outline of the geology of the district shows rocks belonging to all the periods from the Cambrian to the Pennsylvanian, with unconformities separating all the systems except the Cambrian and the Ordovician, where the transition is within the Knox Dolomite, which here attains a thickness of 3,300 feet. An unconformity is found within the Ordovician. Within the area are extensive deposits of red hematite and brown ore, and important beds of coking coal and fluxing limestones.

The red hematite or Clinton ore is found in the Clinton or Rockwood formation which, in Alabama, consists of lenticular beds of sandstone and shale with four well-marked ore horizons. The ores occur in lenticular beds analogous to strata, interbedded with limestone, sandstone, and shale. Three opposing theories have been advanced to account for the origin of the Clinton ores: (1) original deposition; (2) residual enrichment by weathering; (3) replacement by percolating waters. Mr. Eckels shows that both the second and third theories are untenable, and that observations support the theory of primary sedimentary deposition.

The brown ores or ores of the hydrous iron oxides belong to a type common in southeastern United States, occurring as irregular masses associated with residual clays, and underlain by limestones of Cambrian and Cambro-Ordovician age. Mr. Eckel points out very forcibly that the decay of a limestone carrying disseminated iron material would not of itself yield such a deposit of ore, but that some factor must be found whereby the iron is concentrated. In his opinion, this concentration usually took place in the limestone itself.

The coke used in the blast furnaces of the district is made from coal mined in the Warrior coal field which lies to the northwest of the valley.

E. R. L.

Annual Report of the Geological Survey of Western Australia for the Year 1909. By A. GIBB MAITLAND, Government Geologist. Pp. 32, maps 4, and figs. 3.

The report contains a summary of the work done and the results obtained by each of the fifteen officers employed by the survey. Three bulletins were issued by the survey during the year 1909: Bull. 33, "Geological Investigation in the Country Lying between 21 deg. 30 min. and 25 deg. 30 min. S. Lat. and 113 deg. 30 min. and 118 deg. 30 min. E. Long., Embracing Parts of the Gascoyne, Ashburton, and West Pilbara Goldfields"; Bull. 35, "Geological Report upon the Gold and Copper Deposits of the Philips River Goldfield"; Bull. 37, "The Geological Features of the Country Lying along the Route of the Proposed Transcontinental Railway in Western Australia."

E. R. L.

"The Dakota-Permian Contact in Kansas." By F. C. GREENE. *Kansas University Science Bulletin*, Vol. V, No. 1 (October, 1909), pp. 1–8.

The paper presents a summary of the relations of the Permian and the Cretaceous in Kansas, north of the Smoky Hill River.

E. R. L.

Annual Report on the Mineral Production of Virginia during the Calendar Year 1908. Virginia Geological Survey Bull. No. I-A. By THOMAS LEONARD WATSON. Pp. 138.

Virginia possesses an abundance and variety of mineral materials, about forty varieties of which are now exploited, many of them on a large scale. A table of the mineral production in 1908 shows a total value of nearly $18,000,000, of which iron makes up over $6,000,000. Under the heading Preliminary Generalities, the author presents a brief and interesting review of the physiography and general geology of the state, including several generalized sections from various parts of the state. The parts devoted to the various mineral deposits are chiefly descriptive and statistical. A valuable feature of the report is a series of maps showing the distribution in the state of a number of the most important of the mineral deposits.

E. R. L.

Annual Report of the State Geologist, Geological Survey of New Jersey, 1909. By HENRY B. KÜMMEL, State Geologist. Pp. 123.

Besides the administrative report this volume contains the following papers: "Report upon the Development of the Passaic Watershed by Small Storage Reservoirs," by C. C. Vermeule; "Records of Wells in New Jersey, 1905–9," by Henry B. Kümmel and Howard M. Poland; "Notes on the Mineral Industry," by Henry B. Kümmel.

E. R. L.

"A Proposed Classification of Petroleum and Natural Gas Fields Based on Structure." By FREDERICK G. CLAPP. *Economic Geology*, Vol. V, No. 6 (September, 1910), pp. 503–21.

The classification proposed by the author of this paper is based on the "anticlinal" or "structural" theory, which is called into use to explain the segregation of oil, water, and gas from a primary disseminated condition. Depending on the structures which have segregated and localized the pools, seven classes of oil and gas accumulations have been distinguished by the author: I, Where anticlinal and synclinal structure exists; II, Domes or quaquaversal structures; III, Sealed faults; IV, Oil and gas sealed in by asphaltic deposits; V, Contact of sedimentary and crystalline rocks; VI, Joint cracks; VII, Surrounding volcanic vents. Class I embraces most of the known oil fields and is subdivided into five subclasses to distinguish the various relations of the pools with anticlines and synclines.

E. R. L.

"Outline Introduction to the Mineral Resources of Tennessee." Extract (A) from Bulletin No. 2, *Preliminary Papers on the Mineral Resources of Tennessee, State Geological Survey*. By GEORGE H. ASHLEY, State Geologist. Pp. 65.

This pamphlet contains a brief survey of the surface features of the state, the geological formations, and the geological history; and a list of the minerals of the state with a brief notice of their occurrence, use, etc. Bulletin No. 2, of which this is the first part to be published, is the first scientific publication of the newly established state survey, and is not intended as an original contribution but as a brief statement of facts already published, and is designed to meet the demand for immediate information on the mineral resources of the state.

E. R. L.

Summary Report of the Geological Survey Branch of the Department of Mines, Canada, for the Calendar Year 1909. By R. W. BROCK, Director. Pp. 307.

Besides the administrative report of the director of the survey, there is included in this volume a short summary report by each of the geologists and officers of the survey, of the work carried out during the year. Almost all of the work at present being undertaken is along economic lines.

E. R. L.

"The Tectonic Lines of the Northern Part of the North American Cordillera." By W. JOERG. *Bull. Am. Geog. Soc.*, XLII (1910), 161–79. With map.

This paper pictures the tectonic lines of the North American Cordillera from the 40th parallel to Bering Sea. Though the author has based his work in part upon the reports of the geological surveys of the United States and Canada, he has confessedly followed Suess, in the main, both in subject-matter and in mode of treatment. The chief purpose of this paper is to consider in their larger relations the individual ranges and groups of ranges which go to make up this complex system. The interrelations of these mountain chains are discussed in a condensed synoptical form. The axes of the many separate, individual ranges are located on the map by heavy black tectonic lines which show graphically the distribution and direction of deformative movements. A prominent place is given to the mountain systems of Alaska.

In conclusion the author suggests the subdivision of the North American Cordillera from Bering Sea to the Isthmus of Tehuantepec into three major divisions: (1) Northern Cordillera, or Alaskides; (2) Central Cordillera; (3) Southern Cordillera, or Lower California and the Mexican Highland.

The boundary between the first and second divisions would be the zone of coalescence near the Alaskan boundary, that between the second and third the depression along Salton Sink, the Gila, and the Rio Grande. The decided Asiatic structure of the Alaskides is the reason given for recognizing them as an independent major subdivision of the Cordillera.

R. T. C.